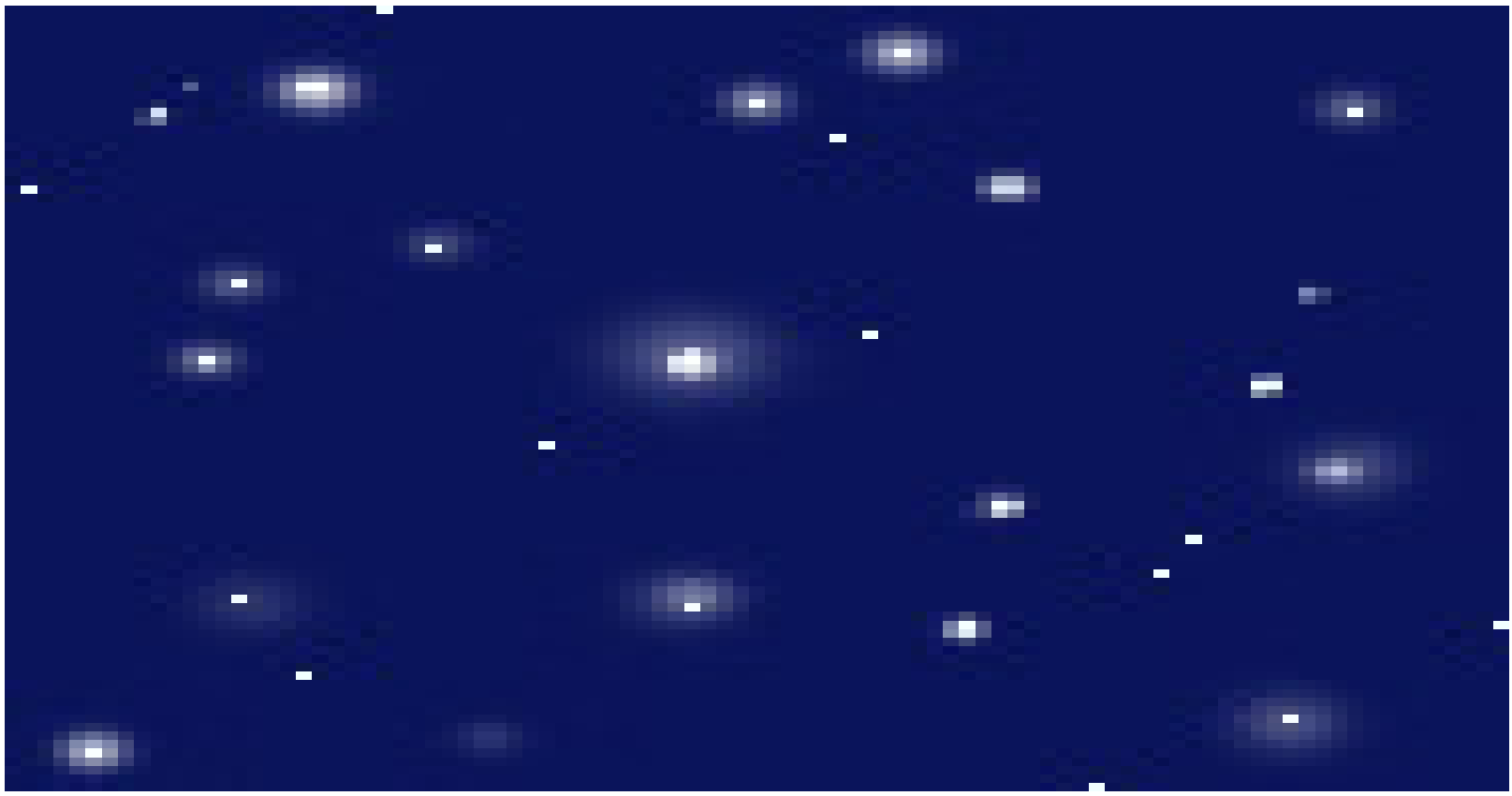

DETECTING ALIEN CIVILIZATIONS

WHAT ARE THE CHANCES?

Detecting Alien Civilizations -- What Are The Chances?

Adjunct Textbook for Introduction to the Natural Sciences

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Table of Contents

Intended audience

Undoubtedly, the question, “Are we alone in the universe?” has been posed for eons. It evokes both hope and dread. We dream aliens might teach us how to live longer, healthier, happier lives, and enlighten us regarding the most persistent mysteries of the universe and our place in it. Then again, novelists and movie/television writers often portray dastardly aliens who would enslave or destroy us.

An objective of this book is to entertain the reader, naturally. In addition, though, it is intended to serve as an adjunct textbook.

Students will find this simplified introduction to relevant topics from the natural sciences especially engaging because they are presented here in the context of this fascinating “Are we alone?” question of current/constant interest. Pre-secondary-education level readers will become excited (or become more excited) about the natural sciences and be inspired to delve further into the debate over detecting alien civilizations. For the same reason, this book could likewise be incorporated into the syllabus of a college/university (elective) science course for non-science majors.

Note that no investigation of the validity of reports regarding sightings of or encounters with aliens visiting our planet is included.

Opening scene

Nancy

There you are. Mom said I'd find you two out here on the porch by yourselves. She said you always hide away from everyone else.

Aunt Peg

Nancy, your mother was right. Your Aunt Alice and I hate everyone in the family -- except you, of course. It will be absolutely forever before dinner will be ready and we couldn't bear the prospect of spending such an interminable eternity listening to the rest of the family carry on.

Aunt Alice

Peg, stop being so sarcastic. Nancy might think you're serious.

Nancy, we're not antisocial. It's just that your Aunt Peg and I only get to see each other once a year, if that, so we have a lot to catch up on.

Nancy

You only get to see me once a year, too. And neither of you made it here for last year's Thanksgiving.

Aunt Peg

We're so sorry, Nancy. My project on the telescope in Chile finally got scheduled last November and astronomers can't be turning down telescope time, no matter when it is offered.

Aunt Alice

And, coincidentally, my team got scheduled on one of the telescopes in Hawaii.

But we're both here now, with our favorite niece.

Nancy

I'm your only niece -- or nephew, or daughter for that matter.

Aunt Peg

Yes, well, your mother was the only one of the three sisters who dabbled along the more traditional path.

So, let's catch up on you now. How is school going?

Nancy

School's fine. I mostly like science. Our science teacher talked about SETI last week. Since you two are astronomers, I'm hoping you can explain to me more about SETI and I can write a report on it for extra credit in class. I'll take notes on my tablet.

Aunt Peg

Uh oh.

Nancy

What? Did I say something wrong?

Aunt Alice

You said nothing wrong.

Peg, behave yourself.

You said nothing wrong, Nancy. We would love to discuss SETI, the Search for Extra-Terrestrial Intelligence -- with the emphasis on the word "discuss," Peg.

Your Aunt Peg and I have "discussed" SETI previously and found we disagreed on the merits of searching for signals from civilizations beyond our planet, Earth.

I think it is a wonderful endeavor. I applaud the many brilliant scientists and technologists who are scanning the heavens for signals which might indicate the existence of alien civilizations. Can you imagine what impact it would have if humans actually detected such a signal? It would be perhaps the single greatest discovery in human history.

Aunt Peg

Both Buddha and Confucius will return, arm in arm, before that happens. It's a foolish waste of valuable resources which could be better spent on any number of other endeavors. The SETI folks have been searching with their telescopes in Puerto Rico and elsewhere for how many years now? -- half a century? more?

Nada. Nothing. Because there's no one out there whose signals we could detect.

Aunt Alice

SETI's capabilities so far have been minimal. There's so much sky to scan and an overwhelming number of types of signals to scan for.

Plus any such signals would certainly be very hard to detect. Imagine you are tuning a radio, trying to find a very faint station while the static on the radio is deafening. The task of SETI is far more difficult than that.

Nancy

Tuning a radio? Radios tune to stations automatically.

Aunt Alice

Uhhh, yeah. That analogy was a bit dated. Let's see if I can come up with another one.

Nancy

No need. I got the idea.

Aunt Alice

As more and more capable telescopes and other tools become available for the search, we'll get closer to either finding evidence of technologically advanced life elsewhere in the universe or give up trying.

Aunt Peg

No. They will never give up. There will always be people who will believe aliens are out there and will keep siphoning off valuable resources for their eternal quest at the expense of real astronomy: learning about what truly is out there.

Aunt Alice

The money funding SETI nowadays is from private sources. It's been years since SETI received any funding from government budgets. If SETI were to shut down, there's no reason to expect those private donors to switch their donations to other forms of astronomy. They are giving their money because they are excited about SETI, not because they are excited about astronomy in general.

Besides, with our galaxy being so vast and billions of years old, it is easy to expect we're not alone.

Discussion of science and religion

Nancy

My Uncle Rod said God created the world less than 10,000 years ago and scientists are full of it when they say it is billions of years old.

Aunt Peg

Your uncle is an inebriated, id...

Aunt Alice

Peg!

Aunt Peg

I warned Betty that his side of the family were du...

Aunt Alice

Peg!!!

Nancy, what your Aunt Peg is trying to explain is that everyone is free to choose to believe whatever they wish to believe. However, those of us who engage in the natural sciences -- such as physics, astronomy, chemistry, biology -- are obliged while doing so to study and learn from only what we observe. The word “natural” in the name “natural sciences” is critically important. Either because the definition of natural science is not taught routinely in school or, more likely, because we generally forget almost all of what we learn in school, too few of us understand what natural science is and is not.

Natural science is not waging war against anyone’s religion. Religion is about the supernatural. The supernatural is, by definition, outside the scope of the natural sciences.

By analogy, suppose one asks an economist, “What can we deduce from the study of economics regarding how long ago the Impressionistic style of painting began?” The economist might offer some personal opinion as to when Impressionism was first established as an art movement, but the economist would have to acknowledge that the question is outside the scope of the study of economics. Similarly, a scientist is free to form a personal opinion as to whether a supernatural being created the universe we observe or actively determines what we observe, but the existence and actions of a supernatural being are outside the scope of the study of natural sciences.

Aunt Peg

Were you able to follow that analogy, Nancy?

Nancy

Yes, I like analogies. They help me understand something new.

Aunt Peg

I'm glad to hear that because there will be lots of analogies coming your way in the future -- on standardized tests.

I want to add one thing to what your Aunt Alice said. Scientists deduced from a great variety of observations that our galaxy, which we call the Milky Way, and our star, which we call the Sun, and our planet, Earth, are all billions of years old. Some people, including your Uncle Rod, apparently, deduced from a religious text that the universe is less than ten thousand years old and, therefore, believe scientists are wrong. However, deductions from those same scientific observations were instrumental in building hydrogen bombs and placing satellites into orbits, among many other examples.

Aunt Alice

So, as I was saying before we went off on this digression, Aunt Peg and I disagree on how likely it is that SETI will be successful.

Overview of the debate

Nancy

You are both astronomers. How can you have such opposite opinions on something related to astronomy, such as SETI?

Aunt Alice

Because, unlike in calculating the age of the universe, there is so much we have yet to discover regarding how likely it is that alien civilizations could be out there, somewhere, and whether any such civilization would be technologically advanced enough to have been transmitting signals we could detect now.

I am overwhelmed by the number of places in our galaxy where life could exist and that so many of those potential habitats could have nurtured life forms for as long as Earth has, and longer.

Aunt Peg

I, by contrast, am underwhelmed by the word “could.”

What I am overwhelmed by is how many conditions have to be just right for any place to have nurtured life like Earth has.

You’ve heard the expression, “The Devil is in the details.” Well, in addition to there being a lot of guesswork in coming up with an estimate of the number of alien civilizations, the assumptions one has to make along the way are bedeviling.

Aunt Alice

Your Aunt Peg is much less optimistic than I am in guessing at the number of civilizations which might be out there in our galaxy and she makes more restrictive assumptions.

Aunt Peg

More realistic assumptions, I would say.

For instance, most everyone claims it is likely that some of the simplest forms of life, such as bacteria, will be common throughout our galaxy wherever conditions allow such simple life to survive. Maybe, but I’m not so sure I agree. My voice might be among those dissenting, winged serpents still flailing to stay aloft in the face of the harsh wind coming from “most everyone.”

Aunt Alice

Why, Peg, I never knew you wax poetic.

Aunt Peg

It’s the only way I will ever wax again.

Nancy

Huh?

Aunt Alice

Never mind. Your Aunt Peg was being a little ... just, never mind.

Consider that once life began here on Earth, amazing forms of life evolved which exist in places no one thought could support life, until life was discovered there -- in the coldest parts of Antarctica, in the hottest and driest deserts, in the darkest caves, and at highly toxic (for us) vents on the deepest ocean floors.

Aunt Peg

We have yet to create even a single-cell organism in the lab or find definitive signs of any form of life, no matter how simple, anywhere other than on Earth. It's a pretty big leap to assume life exists elsewhere just because it exists everywhere on our planet, don't you think?. The initial appearance of life on Earth might have been the result of an extremely unlikely coincidence of freakish events within an unusual or even unique environment.

Aunt Alice

No one knows for sure. But consider, also, it has been conjectured that life in our galaxy might have initially appeared elsewhere and been transported in fragments of rock or ice to seed the rest of the galaxy.

Nancy

That sounds freaky.

Aunt Peg

Definitely freaky. Some life form, even the simplest life form, remained viable for the time it would take to reach Earth from even the closest star in our galaxy, especially with all the radiation in space it would be subjected to during the journey, and survived the collision with our planet when it arrived? Seriously?

Aunt Alice

Alright. But for the purpose of this discussion -- for Nancy's benefit -- we need to agree on the assertion that the simplest forms of life are common throughout our galaxy. If, instead, not even the simplest life form exists anywhere other than on Earth, obviously this discussion is over and your Aunt Peg would be correct that the SETI folks are wasting their time.

Nancy

My Uncle Rod also said no life exists anywhere in the universe except on Earth because God chose to create life only here. Aunt Peg, you and Uncle Rod agree with each other.

Aunt Alice

Nancy, listen carefully and you can hear Aunt Peg's teeth gnashing.

Aunt Peg

Moving right along ...

Nancy, a theme you will hear repeatedly in our friendly, mutually respectful debate on this subject is whether we are drawing too much from what happened here on Earth, both in optimistic points and pessimistic points. Unfortunately, for the purposes of this discussion, what we observe on our own planet constitutes our only example from which we can extrapolate when it comes to imagining what conditions are necessary for life to exist elsewhere and to evolve into civilizations emitting signals we might be able to detect.

And I don't want to hear what your Uncle Rod has to say about evolution.

Aunt Alice

I'm looking on my laptop computer for my notes from the course I taught two years ago. Got it.

I taught a course at the university called "Natural Science for Poets" and devoted several lectures to SETI. It was a course for non-natural-science majors who had to meet the university's requirement of taking at least one year's worth of natural science courses. The kids really got into the topic of SETI. I never saw any of them nodding off during those lectures.

Aunt Peg

You called your students at the university "kids?"

Aunt Alice

It's just that they seem to look younger and younger each year.

Aunt Peg

Might that be because we are looking older and older in the mirror each year?

Aunt Alice

Yeah. Well, growing older is the worst.

Aunt Peg

Except for the alternative.

Aunt Alice

Okay, I agree when you put it that way.

Let’s start building toward an estimate of how likely it might be that there are technologically advanced civilizations in our galaxy whose signals we might be able to detect.

Why restrict to our galaxy?

Nancy

Why limit the estimate to just our galaxy? What about the rest of the universe? We learned there are at least hundreds of billions of galaxies in the universe.

Aunt Peg

Good question. First, we need to back up in order to answer your question.

SETI is searching for signals which technologically advanced, alien civilizations might have emitted in our direction. We are emitting such signals now.

Every text, phone call, or video we send each other which is transmitted through our atmosphere doesn’t stop propagating once it reaches the intended receiver, whether that receiver is on the ground or a satellite in space orbiting the Earth. Every such signal spreads out rapidly. Therefore, some of each signal we send propagating through our atmosphere misses the intended receiver and keeps right on going into space. Eventually, those signals, traveling at the incredibly fast speed of light, could theoretically be detected if someone were to be looking for them with a detecting telescope pointed in the right direction and with the right tuning to that signal. However, and this is critically important, our signals leaking into space continue to spread out, leaving very little of them for anyone out there to detect by the time our signals reach them.

The same holds true for us trying to detect signals from alien civilizations. Their signals -- if they exist -- would likewise continue to spread out, leaving very little of them for anyone here on Earth to detect with our telescopes by the time those signals would reach us. The farther a signal travels before it reaches us, the less of the signal we can collect and the harder it is to detect.

It is already difficult to imagine being able to detect signals from aliens within our own galaxy. It is beyond credible that we could detect signals coming from aliens in other galaxies. Other galaxies are so much farther away from us than are the stars, planets, etc. within our own galaxy.

Nancy

You can see that just by looking at the night sky. When we go camping and the sky is clear at night, the stars in our galaxy stretch across a swath of the sky in a broad streak of white. That’s why our galaxy was named the Milky Way by ancient people,

even though they had no idea what a galaxy was back then. But each of the other galaxies is just a tiny dot in the sky.

Aunt Alice

I like the way you explained that, Nancy. I will use that the next time I teach the Natural Science for Poets course. I'll give you credit, too. Then you will already be on your way to becoming a famous astronomer.

Aunt Peg

Yes. As I was saying, it is already barely plausible to detect a signal from within our own galaxy. If that same signal had come to us from even the closest galaxy, Andromeda, it would be at least a thousand times fainter.

Aunt Alice

However, if a civilization in one of the nearest galaxies, like Andromeda, were capable of harnessing much greater power than we currently can, and intentionally directed that power toward us as a signal, it might be plausible to detect it. Admittedly, though, that's a stretch.

For today's purposes, your Aunt Peg and I will both agree it is reasonable to consider only our own galaxy in estimating the likelihood of there being technologically advanced, alien civilizations whose signals we might detect.

Nancy

Got it. What's the first step?

Getting started

Aunt Alice

Nancy, you tell me. How do you suppose we might start?

Nancy

Hey, no one said this would be a pop quiz.

Aunt Peg

It's not a quiz. It's the Socratic method of teaching. You will understand all this better -- and you will get a better grade on your extra credit report, I assure you -- if you

try to figure something out first, rather than merely have it spoon-fed to you. We don't expect you to know this. If you did, you wouldn't have asked us about it. So, don't be afraid of answering incorrectly.

How do you suppose we might start to estimate the likelihood of there being other civilizations in our galaxy emitting signals we could detect?

Nancy

Maybe we could figure how many planets there might be in our galaxy where such civilizations could be living?

Aunt Alice

Good. However, let's think in terms of potential "habitats" rather than just "planets." Moons of planets, for example, could also be plausible habitats.

Now, Nancy, in order to figure how many potential habitats there might be, let's first compile a list of what such habitats would need.

What are the criteria a potential habitat would need to satisfy for it to plausibly harbor a technologically advanced civilization?

Aunt Peg

There are so many criteria any potential habitat must meet for a technologically advanced civilization to evolve there. Can you think of any off the top of your head, Nancy?

Need liquid water

Nancy

We learned that the oldest evidence found of life on Earth indicates life first appeared in the ocean, so you have to have liquid water, right?

Aunt Peg

Excellent first choice. Liquid water is called the universal solvent, meaning more substances can dissolve in it than in any other, naturally occurring substance we know of. All life on Earth relies on water's ability to foster chemical reactions among the substances dissolved in the water, including inside the cells of our own bodies.

In other words, it is hard to imagine any simple life form and especially any advanced creature evolving from any simplest life forms without liquid water.

Aunt Alice

Is it -- like you said -- hard to imagine evolution without liquid water, or is it just easier to decide evolution needs liquid water because the only example of evolution we have ever seen happened on our own planet in the presence of liquid water? Now it's my turn to go out on a limb and question how big of a leap it is to jump from our only known example of Earth to the whole galaxy. There are other solvents besides liquid water and chemical reactions occur even in the atmosphere.

Ammonia is probably the second-best solvent when it is in an environment where the combination of temperature and pressure cause it to pool in liquid form. For those potential habitats where ammonia is a liquid, there might be life forms based on ammonia instead of water.

Aunt Peg

Water is less dense when it freezes into ice than when it is liquid, so ice floats on water, creating an insulating layer at the surface of bodies of water. This inhibits deep oceans of water from freezing in their entirety anywhere on Earth today. Advanced life forms would not have evolved in the oceans if the oceans had frozen through and through. If you conjecture that different, advanced life forms could have evolved in a habitat where some other solvent enables life, wouldn't that other solvent also have to be less dense in solid form than in liquid form in order to likewise protect oceans of that solvent from completely freezing during cold periods?

Aunt Alice

That's a good point. Looking that up now ... no, ammonia is more dense in solid form than in liquid form. Frozen ammonia would not float on top of an ocean of liquid ammonia and thereby hinder an ocean of ammonia from freezing in its entirety.

Other solvents besides ammonia have also been proposed as potential replacements for liquid water in dramatically different life forms. In any event, the consensus among astro-biologists studying the possibility of finding life other than on Earth is to look only where there is a good chance of finding liquid water, so let's agree on this requirement.

Nancy

Okay. Got it. Please text me with what you learn about other solvents.

Aunt Alice

Ummm, ya know, Nancy, come to think of it, researching alternate solvents could be an exercise left to the student here.

Nancy

Yeah, but I would be more likely to miss something and then you would be giving incomplete information the next time you teach that Natural Science for Poets course.

Need to be in the Goldilocks Zone

Aunt Peg

It appears our niece is rather clever.

Continuing undaunted, for there to be liquid water on a potential habitat, the habitat needs to be neither too close to its star or the water will eventually boil away into steam from the heat, nor too far from its star or the water will always be frozen. Astronomers refer to this by saying the habitat's orbit around its star has to be located in the "Goldilocks Zone" of its star. Earth is in the Goldilocks Zone of our star, the Sun.

Aunt Alice

That's true if you require that the necessary liquid has to be on the surface of a habitat. But astronomers suspect there could be oceans of liquid water on habitats which are not in the Goldilocks Zones of their stars; hidden under a protective surface of rock, for example. The surface could be keeping the water from boiling off if the habitat is too close to its star. If too far from the star, heat from the core of the habitat could keep the water in liquid form, insulated by the solid surface from the sub-freezing temperatures at the surface.

It appears this is happening even within our own Sun's solar system -- a star's "solar system" being defined as everything orbiting around the star. There is strong evidence that one of the moons of the planet Jupiter, called Europa, and one of the moons of the planet Saturn, called Enceladus, each spew water from geysers on their surfaces. That suggests strongly that liquid water exists under the surface of those moons.

Jupiter and Saturn are both outside the Goldilocks Zone, being much farther away from the heating provided by our Sun than Earth is, and both of those two moons have surfaces which are frozen. And there are more places in our solar system which are showing signs of possible liquid water below the surface, albeit based on less compelling evidence, so far.

Aunt Peg

Fine, but remember that the ultimate goal here is to estimate the likelihood SETI, or whoever, could detect signals from a technologically advanced civilization. How likely

could such a civilization evolve when confined under a thick surface of a moon or planet?

Nancy

That sounds like a miserable existence.

Aunt Alice

It doesn't sound attractive to us, but if there are creatures who know of no other environment than their own, it might work for them.

Analogously, we look back condescendingly at humans on Earth living in primitive, hunter-gatherer tribes, fending off animal predators with sticks and stones, and succumbing to all forms of disease and maladies because they had no medical knowledge. But that was their situation and they had no idea what it would be like to be living as we do today.

Aunt Peg

Right. Because our medical knowledge is so vastly superior that we produce an endless stream of medical studies which either contradict prior medical studies or will be contradicted by future medical studies. Now that's progress.

Aunt Alice

You are so sarcastic at times, and cynical.

Aunt Peg

Forget thee not the immortal words attributed to George Bernard Shaw, "The power of accurate observation is commonly called cynicism by those who haven't got it."

Nancy

I've got to write that down!

Aunt Alice

Are you happy now, Peg? You have contributed to the corruption of a minor.

Nancy

Too late. I already love sarcastic humor.

So, if a habitat is in the Goldilocks Zone, it has liquid water on its surface.

Need to get water

Aunt Peg

Not necessarily. Can you think of why it might not?

Nancy

Because aliens came with their giant spaceships and sucked all the water from the habitat because the aliens thought they polluted all the water on their home planet because the universe is only a computerized simulation but there was a glitch in the program that caused the aliens to think they polluted all their water even though they actually hadn't.

No?

Aunt Peg

I kind of like your sci-fi plot; although, I think I detected in it a hodgepodge of plots I've already seen in several dystopian movies. But, no. The buzzer sounded. Sorry, try again.

Nancy

Well, does every habitat come with its own water?

Aunt Peg

There you go. First, consider how Earth got its water.

Astronomers can see with our telescopes the formation of stars elsewhere in our galaxy. Stars with their solar systems form from huge, massive clouds in the galaxy comprised mostly of hydrogen. Many of these clouds also contain atoms and molecules incorporating other elements besides hydrogen, such as oxygen.

Most of that mass within what becomes a solar system coalesces from mutual gravitational attraction among the atoms and molecules into a large clump at the center. Mutual gravitational attraction increases with increasing combined mass and decreases the farther away objects are from each other. If there is enough mass at that central clump, the clump eventually becomes dense enough for nuclear fusion to begin there; that is, fusing hydrogen nuclei into helium and emitting energy in the process. Then, behold, a star is born!

Fusion in the core of such a newly formed star radiates that energy in various forms, including as visible light, which propagates out of the young star and shines in all directions.

Whatever mass within the solar system does not coalesce into the central star can coalesce gradually, also by gravitational attraction, into planets and moons and asteroids and comets, all circling the central star. However, while the planets and other heavenly bodies are coalescing, when the star begins fusion, the resulting radiated energy from the star pushes away residual, freely floating, lighter atoms and molecules located relatively near the star.

So, almost all water molecules in our own early solar system not captured by the Sun would have been blown out of the Goldilocks Zone and ended up in the colder, outer parts of our coalescing solar system, away from where Earth was forming. Then later, so the thinking goes, asteroids (and comets to a lesser extent), which formed out where the water molecules were pushed to, bombarded the early Earth, carrying their water to our planet.

Nancy

Why isn't that still happening now?

Aunt Peg

It is. There are molecules, bits, chunks, and sometimes good-sized pieces that collide with Earth daily, even now. One estimate I read claimed something like a quarter of a million pounds of stuff enters the Earth's atmosphere from space each day.

But that's a drop in the bucket compared to the amount of water-bearing stuff that would have had to bombard Earth billions of years ago to give us the vast oceans and other bodies of water we see today. What in the distant past might have caused such a massive bombardment of Earth from the outer regions of our solar system?

One plausible explanation is that water-bearing asteroids which were far more numerous in our early solar system, were displaced from their orbits around the Sun when the gravity of one or more large planets in those outer regions of our solar system flung huge numbers of asteroids toward the inner solar system, where Earth is. The gravity from a large planet would pull a smaller body, such as an asteroid, toward it. If a smaller body doesn't simply slam into the large planet -- and most wouldn't -- the smaller body would get flung away in some direction. In our solar system, Jupiter and Saturn are large planets which could have played that role.

This concept of large, distant planets causing water-bearing bodies to bombard the planets and moons closer to the star is a conjecture based on theoretical models of the early solar system. As of now, this concept lacks incontrovertible, supporting evidence. However, if it's true, wouldn't it be necessary for large planets to form far away from a star, out where there would be plenty of water? How likely might it be that other solar systems would also have large, distant planets deflecting water-bearing objects into their Goldilocks Zones?

Aunt Alice

We don't know yet, of course, although I know of no reason to doubt that large planets could form out where water molecules would be present in other solar systems. But there are also other plausible explanations, too, for how Earth got at least some of its water.

Recent evidence suggests that a significant fraction of the water in and on Earth had already accumulated within heavier clumps of rock orbiting around the Sun which eventually aggregated into Earth. So, when the Sun's radiation started, the water in those heavy clumps did not get pushed out of the Goldilocks Zone where Earth formed. That process could occur in other solar systems, too.

In addition, comets, which in our solar system formed far beyond Jupiter and Saturn, could have brought water back to the Goldilocks Zone. A passing star or black hole could have likewise disrupted the orbits of a huge number of water-bearing comets. That could also happen in other solar systems.

Nancy

Why would there be a passing star or black hole?

Aunt Alice

With our telescopes, we can see galaxies merging together out there in the universe. A merger between two galaxies will result in very few collisions among stars because solar systems are very far apart from each other -- most of a galaxy is essentially empty space. However, the gravitational effects as stars and plausibly black holes in the galaxies pass by each other, even at large separation distances, would most likely disrupt where stars end up within the combined galaxy and potentially perturb the orbits of bodies orbiting their stars.

There is evidence suggesting our galaxy absorbed other, smaller galaxies in the distant past. And our galaxy is on a course to merge with a larger, neighboring galaxy, Andromeda, due to arrive in roughly four to five billion years.

Nancy

I know billions of years is an extremely long time. Still, the thought of our galaxy "merging," as you say, or "colliding," as I would call it, is frightening.

Aunt Alice

The universe is a wondrous thing to study, full of incredible surprises, with many more yet to be discovered and understood by the next generation of astronomers who are smart and curious. Hint, hint.

Another plausible way to get water on a habitat within the Goldilocks Zone is for a planet with its moons to form farther out where the water molecules are plentiful and then migrate inward, toward its star, into the Goldilocks Zone.

Nancy

Whoa. What a minute. Planets migrate? They don't stay in their orbits?

Aunt Alice

Evidence and modeling with computer simulations suggests planets are not necessarily fixed in their orbits. Their gravitational fields interact with each other, for one thing, which can cause one or more planets in a solar system to drift to an orbit farther away from that solar system's star, or closer.

We have seen evidence of other solar systems with giant planets similar to our Jupiter, but orbiting very close to their stars. Theoretically, there should not be enough of the original cloud from which a solar system forms so close to a star to aggregate together into a giant planet. The star gobbles up too much of the stuff closest to it for giant planets to form near the star. Therefore, we figure those planets must have formed much farther away from the star and migrated inward.

Nancy

I read about a recent satellite that was launched. The satellite had to use on-board propulsion jets to circularize its orbit around the Earth. Otherwise, it would soon come crashing back down and, "Oops," there goes another billion dollars, or whatever. If a planet changes its orbit from one distance away from its star to a different distance, doesn't it have to re-circularize its orbit or else it will never be in a stable orbit again? But planets have no on-board propulsion to do that.

Aunt Alice

Insightful, my dear niece. You are correct, if we are considering relatively abrupt changes in orbit, like what happens to asteroids and comets when they are subjected to a powerful gravitational field from a large planet or passing star, as we just discussed. Then, too, if asteroids or comets crash into each other, that would similarly change their orbits abruptly.

However, we're talking about a very slow drift of an orbit. Our Moon, for example, is getting farther from Earth by less than two inches per year.

I mentioned the concept of planet migration only to demonstrate there are multiple ways in which a habitat within the Goldilocks Zone could obtain water. My point is that it is plausibly common for habitats in Goldilocks Zones to have water.

Need to stay in the Goldilocks Zone long enough for advanced civilization to develop

Aunt Peg

Bringing up the topic of orbit drift, or migration, also suggests a related point. If a habitat is in a Goldilocks Zone, does it stay there?

Nancy

Well if planets and moons change their orbits gradually, I guess not.

Aunt Peg

Correct, but there's more. As stars get older, the warming power they radiate gradually changes.

Recall that the Goldilocks Zone is defined as the region not too far nor too close to the star so that the star's radiated energy can potentially keep a habitat in that zone from being too cold or too hot for life to flourish. Therefore, as the radiated power of the star changes, the location of the Goldilocks Zone changes, too. Unless the orbit of a planet just happens to drift in synch with movement of the Goldilocks Zone, a planet inside the zone won't remain inside the zone indefinitely.

Nancy

If everything happens very slowly -- both planet migration and changing star power -- couldn't a civilization develop adequate advanced technology in time to survive those changes?

Aunt Peg

That is certainly plausible, but would a civilization evolve quickly enough so that it can develop such technology in time? It took nearly five billion years since our solar system began to form for our civilization to develop the technology we have. Earth remained inside the drifting Goldilocks Zone all that time. Our Sun has been getting hotter and the prediction is that Earth will no longer be in the Goldilocks Zone roughly a billion years from now. Therefore, if it had taken about a billion years longer for a species on Earth to develop advanced technology than it did, there would not have been such a species on Earth to plausibly survive the changes.

If there is life elsewhere in our galaxy, would evolution there have proceeded as quickly as it did on Earth? Would those habitats have remained in their stars' Goldilocks Zones at least as long as Earth has?

Furthermore, a star like our Sun is expected to "live" for roughly ten billion years.

Aunt Alice

Let’s defer talking about different types of stars and how they evolve until later. Suffice it to say for now that we need to consider how quickly a technologically advanced civilization might develop versus how long its habitat might remain in the Goldilocks Zone of its star.

Aunt Peg

Fine. How about another question for our highly intelligent niece?

Nancy

You’re setting me up for a fall, or a fail.

Aunt Alice

There is no falling and certainly no failing here.

The next topic in my course was this: even after getting water, what could cause a habitat to lose it again? Mars is in the Goldilocks Zone, but there is no liquid water on its surface. Whatever process put water on Earth should have put water on Mars, wouldn’t you expect? And there are features we see on Mars which suggest liquid water once flowed on the surface there. How did Mars lose the liquid water on its surface?

Need to maintain atmosphere to keep liquid water on its surface

Nancy

I’m thinking.

Aunt Peg

Here’s a hint. There’s no liquid water on the surface of our Moon, either. Could you breathe on the Moon, or on Mars?

Nancy

There has to be an atmosphere for liquid water to be on the surface of a habitat in the Goldilocks Zone?

Aunt Alice

Yep. Without an adequate atmosphere to exert downward pressure on the surface of the habitat, water molecules on the surface would eventually float off into space -- in effect, boil away.

Need adequate gravity to keep an atmosphere

Aunt Peg

Which leads to the next question.

Consider that the mass of Mars is ten times the mass of our Moon. There's no appreciable atmosphere on our Moon, but there is a small amount of atmosphere on Mars, although not enough for liquid water to pool on the surface. The mass of Earth is ten times the mass of Mars. There is lots of atmosphere on Earth keeping our water from escaping into space.

So, put all those facts together and tell us what do you suppose a habitat in the Goldilocks Zone which received lots of water during its formation needs in order to have an atmosphere that will hold onto its water?

Nancy

The more massive an object is, the more gravitational attraction it exerts on everything else. I guess the answer is gravity. For liquid water to be on the surface, a habitat would need some minimum amount of gravity to hold its atmosphere in place so it can keep its water.

Need adequate magnetic field

Aunt Peg

Very good. Now let's try a tougher question. Any idea what else is needed to keep its atmosphere? Here's another hint. Earth has the Northern Lights and Southern Lights, which are called the Aurora Borealis and the Aurora Australis, respectively. Mars has almost no aurora. Our Moon has none.

Nancy

I want so much to see the aurora some day. I read about it a lot and the videos are incredible. The Earth's magnetic field protrudes out into space and deflects charged particles coming from the Sun so that the particles head toward the north and south magnetic poles where the Earth's magnetic field dives back into the planet.

You were hinting that a magnetic field is needed to keep an atmosphere. But why?

Aunt Alice

You were about to answer your own question until you stopped too soon talking about the aurora. How do the charged particles which end up at the poles cause the aurora lights?

Nancy

The particles bang into the atmosphere above the poles, dumping lots of energy into the molecules in the atmosphere and those molecules release the energy in the form of light -- gorgeous, spectacular, colors dancing in the sky. I want to go.

Aunt Alice

I understand. You really, really want to see the aurora. And seeing videos of aurora lights just isn't enough for you.

Meanwhile, think about what would happen eventually to the Earth's atmosphere if all the charged particles which the Earth's magnetic field currently deflect were to come slamming broadside into our atmosphere, instead.

Nancy

I could watch the aurora when we go camping and not have to go near the North Pole and freeze my butt off.

Aunt Peg

Someone seems to have a one track mind.

Those streaming, highly energetic, charged particles, which we call the solar wind, would deposit so much energy into the molecules of our atmosphere that this would cause the atmosphere to, again, in effect, boil away into space.

Other stars similar to our Sun likewise emit solar winds. A potential habitat would need a strong enough magnetic field -- not just strong enough gravity -- to keep its atmosphere.

And by the way, those highly energetic, charged particles in our Sun's solar wind would also endanger life's ability to survive and evolve into advanced forms here on Earth if not for Earth's magnetic field being strong enough to deflect as many of the particles as it does. Without Earth's protective magnetic shield, the only life on this planet might have been single cell organisms cowering well under the surface, beyond the reach of the solar wind.

Nancy

What generates our magnetic field?

Aunt Alice

That smirk betrays that our niece thinks she can avoid being asked questions if she asks them first. Not so fast, oh very clever young lady. Meet us half way. You learned about magnetism, didn't you? How is a magnetic field generated?

Nancy

Certain metals, like iron, can be made into a magnet if the atoms in the metal are in a magnetic field which lines them up in one direction.

Aunt Alice

The other way to generate a magnetic field is by flowing charged particles, like when a current of electrons flows through a wire.

Deep inside the Earth, it is believed that liquid iron is flowing, driven by the tremendous heat there. That functions similar to a current in a wire and it generates Earth's magnetic field.

Nancy

Why is it so hot down there?

Aunt Alice

Recall that we were talking earlier about how a star and everything which orbits it form from a cloud of stuff coalescing into larger and larger clumps. As the growing clumps slam into each other to coalesce into even larger clumps, the collisions produce lots of heat.

Recall also that we talked about the bombardment of early Earth and other inner planets by water-bearing asteroids and comets. Those collisions likewise produced a great deal of heat.

Early Earth was a cauldron, so hot that the surface at that time was molten. In a large liquid ball suspended in space, the densest materials tend to sink to the core. Iron is among the densest elements. Not surprisingly, a large ball of molten iron formed deep inside early Earth.

Nancy

That heat hasn't all radiated away into space by now? It's been billions of years.

Aunt Peg

The composition and size of Earth has maintained interior temperatures hot enough to keep the molten iron flowing down there all that time.

Aunt Alice

... and we expect for a considerable time to come.

Also, some fraction of that heat in our molten core is being replenished by the natural decay of any radioactive elements which originally coalesced into our planet.

Many radioactive elements are among the most dense of the elements, so they would have tended to sink toward the core of the planet before our Earth cooled. Uranium, for example, need not be put into a nuclear reactor to spontaneously split apart into lighter elements and emit energy, especially in the form of heat. Splitting of radioactive atoms happens naturally -- using uranium in a nuclear reactor merely hastens that natural process to produce heat at a high enough rate to power turbines to generate electricity.

Aunt Peg

Even still -- and I repeat -- the composition and size of a potential habitat has to be such as to maintain its interior temperature hot enough to keep the molten iron flowing to produce the magnetic field which shields life forms from the onslaught of the solar wind.

Oh, and all that heat also powers plate tectonics, the cracking of the Earth's crusts into plates and the movement of those plates, as if they were sheets of ice on a frozen pond. And what does plate tectonics give us?

Nancy

Earthquakes.

Aunt Peg

Right, and volcanoes, among other related things.

Aunt Alice

Compare Earth to Mars, again. Mars would be expected to have a composition of elements similar to Earth, having formed in a region close to Earth where comparable types of atoms and molecules were present. But Mars has a negligible magnetic field compared to Earth. Because Mars is much smaller than Earth, it cooled off more quickly

than Earth. If you have a small pot of leftovers after a cooked meal, the pot will take a while to cool off enough to put away in the refrigerator. If you have a large vat of leftovers, it will take much longer to be cool enough to go in the refrigerator.

Mars probably had a stronger magnetic field while it was hotter inside, but it's magnetic field dissipated as it cooled, presumably because there is so much less heat in its core now to keep liquid-iron flowing there.

Similarly, Mars has far less plate tectonics compared to Earth, again because it cooled off more rapidly. Plate tectonics will come up again later as we continue this discussion. Hang on to that concept.

Aunt Peg

In the meantime, though, the moral of this story is that even if a habitat has the right ingredients to create an adequately powerful magnetic field, advanced life is not going to develop there if the interior heat dissipates too quickly relative to the time it takes for advanced life forms to evolve.

Oh, and timing might be important, too. At first glance, one would think water brought to a molten Earth during bombardment by asteroids and comets, would simply be blown away by the solar wind as it arrives. An adequately strong magnetic field and adequately strong gravity need to be present already during that bombardment to hang onto the water.

Need right amount of oxygen

Aunt Alice

Next, let's talk about the required atmosphere.

The atmosphere must be capable of more than just keeping water in liquid form on the surface of the habitat. It has to nurture the evolution of advanced life forms.

Nancy

We have to breathe. So there has to be oxygen in the atmosphere. That's a no-brainer.

Aunt Peg

Ahhh, but is it that simple? Yes, we breathe in oxygen, pass it into our blood via our lungs, distribute the dissolved oxygen throughout our bodies, and all our cells require such a continuous supply. Clearly we need a minimum amount of oxygen in our atmosphere to breathe or we die.

I'm sure you've watched plenty of movies and shows -- and not just dystopian ones -- so you've often seen plots which include someone in danger of suffocating when she is trapped in an air-tight location. The oxygen she is inhaling -- and exhaling as carbon dioxide and water vapor -- can't be replaced without air from outside. Will she survive? Will she be rescued in time? I can't stand another minute of this overly-dramatized tension.

Aunt Alice

Neither can we.

Aunt Peg

Oh alright.

But would any-old amount of oxygen in the atmosphere be acceptable? Too much oxygen is not good, either, because oxygen feeds fire. Higher concentrations of oxygen in the air would make the world more flammable.

Aunt Alice

Peg, I came across that argument, too, when preparing to teach my Natural Science for Poets course. The claim is that the oxygen content in the air needs to be maintained at a habitat within some narrow range for advanced life to evolve there. I do not find that argument compelling.

The oxygen content in our air at sea level today is about 21% -- one part in five. Evidence indicates it was significantly higher, more like 30% or so, when dinosaurs walked the Earth. Fossils of plants growing then show that vegetation did fine, even if forest fires might have burned more often and hotter back then. It seems that life forms on Earth adapted to a fairly wide range of oxygen content in the atmosphere.

Aunt Peg

Seen any technologically advanced dinosaurs lately?

Are you confident advanced technology would have been developed on Earth at those higher levels of oxygen in the atmosphere?

Aunt Alice

We can't know whether advanced civilizations could have evolved here on Earth had the oxygen content remained that high, or evolved elsewhere with relatively elevated levels of oxygen in the atmosphere, either. I just don't see a good reason why not.

Going out on a limb now, again, was oxygen required at all? There was no appreciable, free oxygen in the atmosphere of Earth initially and yet life forms, called anaerobic organisms, existed on our planet then. There are still anaerobic organisms today.

Aunt Peg

Seen any technologically advanced anaerobics lately?

There was a huge proliferation and diversification of life forms on Earth once the earliest photosynthetic life forms evolved and started putting significant amounts of oxygen into our atmosphere. I don't think that was a coincidence. That suggests strongly there had to be at least some minimum amount of oxygen in the atmosphere of a habitat for there to be any reasonable chance of evolution leading to advanced civilization.

What about another key role oxygen serves? Ozone is a molecule consisting of three oxygen atoms bonded together instead of just the usual two in an oxygen molecule. Ozone molecules in the upper atmosphere absorb ultraviolet light from the Sun, plus the chemical reaction which forms ozone from oxygen also absorbs ultraviolet light from the Sun. Without that absorption, there would be too much ultraviolet light reaching the surface of our planet which would do major damage to living organisms. Hence, without enough oxygen in the atmosphere to be converted into ozone, there would not be adequate protection from ultraviolet.

Nancy

If we evolved in the presence of much more ultraviolet, wouldn't we have evolved with fur to protect us from ultraviolet, or some such adaptation?

Aunt Peg

That's certainly plausible. Good point.

Nancy

Really? Wow. Thanks.

Aunt Alice

Let's agree that it is reasonable to presume a habitat would need oxygen in its atmosphere to foster an advanced civilization. But we have no idea what the range of minimum required to maximum acceptable oxygen in the atmosphere would be here on Earth, let alone at other potential habitats.

Aunt Peg

Alright, but there is more to this topic of oxygen in the atmosphere. How do we get free oxygen molecules to breathe? As far as I know, the only naturally occurring process on Earth is from photosynthesis in plants and plant-like life forms, like algae and certain microbes, which absorb carbon dioxide from the air, use it along with water and sunlight to yield the energy they need to live; and then release oxygen molecules into

the air as a byproduct of the process. However, I read that some biologists think the photosynthetic mechanism is so complicated that it might have evolved only once, that being on our own planet.

Aunt Alice

Yes, there are scientists who jump to that uniqueness conclusion about photosynthesis and also about the advent of the first cell and maybe other, similar conjectures, too. I wonder how much of that kind of thinking is based on hubris -- you know, the desire to think we humans and our world are super special. Or maybe just a lack of imagination. I don't know.

How about we list as one of the requirements for a habitat that photosynthesis, or some equivalent mechanism, is taking place to put oxygen molecules into the atmosphere? We'll leave until later the guessing of how likely it is that photosynthesis or its equivalent exists at a habitat and whether the resulting oxygen level in the atmosphere would be the right amount.

Need right amount of components in atmosphere which produce greenhouse effect

Aunt Peg

Sounds good to me.

Then there's the question of how much carbon dioxide in the atmosphere is the right amount.

Nancy

Are we going to talk about the greenhouse effect now? How does that fit in here?

Aunt Alice

There are naturally occurring processes which maintained the carbon dioxide levels on Earth fairly stably over our planet's relatively recent history. Carbon is naturally introduced to the atmosphere by volcanic activity spewing it from below the surface of our planet. Balancing against that, the multitude of carbon-based life forms on our planet suck up carbon during their lives and take that carbon to their graves -- so to speak -- when they die. Depending on several factors, including where and how they die, that carbon might gradually turn into coal or oil or natural gas -- so-called "fossil fuels," buried under the land or beneath bodies of water. Also, erosion of certain types of rocks releases "silicate minerals," which chemically react with carbon to lock the carbon away in the form of "carbonate minerals."

In the distant past, when the carbon dioxide level in the atmosphere gradually rose, our planet's temperature gradually rose as a result. Higher planet temperature is a measure of higher energy in the bodies of water and in the land and in the atmosphere. The higher energy induced more rain and greater winds, which caused gradually faster erosion. The higher rate of erosion released silicate at a higher rate. The increasing levels of silicate reacted chemically with the increased level of carbon dioxide to gradually remove carbon dioxide from the atmosphere at a higher rate and thereby gradually

brought carbon dioxide back down to lower levels. With gradually less carbon dioxide left in the atmosphere, Earth's temperature gradually fell back, climate gradually reverted, and so erosion gradually went back to the prior level, too.

And if, for some reason, the carbon dioxide level in the atmosphere gradually decreased, the opposite of this process would gradually bring it back up. These are natural mechanisms to keep the climate relatively stable. Nice, huh?

Nancy

Then why all the fuss nowadays about greenhouse gasses, and especially carbon dioxide causing climate change? Erosion of rocks will take care of the problem.

Aunt Peg

Nancy, what word did you notice Aunt Alice use over and over again in her explanation -- so much so as to be annoying, even?

Aunt Alice

Annoying? Really?

Nancy

Gradually I heard Aunt Alice say "gradually" more and more gradually, but it was gradual.

Aunt Alice

You two are ganging up on me now. No fair.

Aunt Peg

But "gradually" is the key difference between how the Earth kept its atmospheric level of carbon dioxide relatively stable for so long, versus what's been happening since humans discovered how to burn those fossil fuels at prodigious rates, releasing back into the atmosphere incredible amounts of the carbon that was sequestered away over millions of years. The natural chemical processes which lock away carbon into carbonate minerals take many thousands of years to GRADUALLY compensate for increasing carbon dioxide levels. That's why all the fuss.

Our neighboring planet, Venus, is in the Goldilocks Zone, like Earth is. But Venus became the victim of a runaway greenhouse condition. It has so much carbon dioxide and other greenhouse-effect causing molecules in its atmosphere that the surface of that planet is hot enough to melt lead. It would not be in our best interests -- to put it mildly -- if we humans continue to push our planet toward a runaway greenhouse condition, too.

Nancy

Is it that bad? What kind of world will I be living in?

Aunt Peg

There are already major problems as a result of Earth warming and there will definitely be worse problems in the future. That's inevitable at this point.

Aunt Alice

Still, “hope springs eternal,” as optimists like to say.

But, I’m not going to sugar coat this for you, either, Nancy. The longer it takes for human civilization to vigorously reduce carbon-emitting human activities, especially our burning of those fossil fuels which sequestered carbon in the Earth for millions of years, the worse the problems will be before we can make it better.

Aunt Peg

On that cheery note, getting back to our discussion, the carbon dioxide level in the atmosphere of a potential habitat has to fluctuate no more than moderately over very long periods of time for technologically advanced civilizations to have any chance of evolving there. Despite rudimentary life forms existing on Earth in hot water vents at the bottom of the ocean and in hot springs in places like Yellowstone National Park, advanced life on Earth evolved only within a relatively narrow temperature range from not much below the freezing point of water to less than roughly 120 degrees Fahrenheit.

Aunt Alice

True, yet there only needs to be moderate temperature in one or more regions, not the entire potential habitat. Life forms can migrate if climate changes gradual..., slowly enough.

Continuing with my course notes, Nancy,

Nancy

I sense the imminent approach of yet another quiz question.

Need dry land

Aunt Alice

Nancy, you are about to send out a signal which could potentially be detected elsewhere in the galaxy. What do you need to send that signal?

Nancy

A transmitter, of some sort.

Aunt Alice

Made of what?

Nancy

I guess metal and plastic, and other stuff.

Aunt Alice

And what is the power source for your transmitter?

Nancy

Electricity. I plug it into an outlet.

Aunt Alice

If you lived entirely in the ocean, how could you have built a fire hot enough to melt metal or form plastic? Could you have learned how to generate and harness electricity?

Nancy

Nope. The habitat would need dry land for anyone to do those things.

Aunt Peg

Similarly, no creature evolving strictly in gas -- the atmosphere -- can do those things, either.

Nancy

Isn't dry land common?

Aunt Peg

Not necessarily. Recall we talked about how planets and other bodies in a solar system can be extremely hot when they are first forming due to coalescing masses slamming into each other and/or the bombardment by asteroids and comets. In the early stages, therefore, a rocky planet can be a molten sphere, held together by its own gravity. Water, being less dense than most everything else in the planet, would end up floating nearer the surface. As the planet cools down, if it is in the Goldilocks Zone and there is enough water and atmosphere and gravity and magnetic field -- all like we discussed before -- the water would spread itself over the entire surface of the planet as an ocean. Hence, no dry land anywhere on the surface.

Nancy

So how did we end up with dry land on Earth?

Aunt Alice

That's where your plate tectonics and vulcanism come into play. Remember them? If the potential habitat maintains enough internal heat after the rocky crust of the habitat cools down, the molten rock deep inside the habitat, driven by tremendous heat there, forces the rocky crust under the originally uniform ocean to split into plates and then propels those plates to move against each other. Near the boundaries among these plates and sometimes elsewhere at soft spots in the planet's crust, the molten rock can find its way to the surface and spew out as volcanoes. Also, plates can be pushed against each other with such great force as to pile one up over another. Wherever molten rock flows to the surface or rocky crust gets thrust up, you get plateaus and mountains which can poke up above the water on the surface. That's how you get dry land. That's how we got dry land on Earth.

Aunt Peg

Meanwhile, erosion from wind and rain wears down and washes away the dry land back into the ocean. It's a tug of war between tectonic activity with vulcanism driven by interior heat which build up land versus weather tearing it down again. Depending on how quickly the habitat's interior cools, dry land might be gone by the time evolution brings about creatures capable of developing advanced technology. Or, if too much water accreted onto the habitat, the tectonic activity and vulcanism might not be enough to push any of the crust above a very deep ocean covering the entire habitat.

Need metals near surface

Aunt Alice

Vulcanism serves another critical purpose. Go back to your transmitter, Nancy. Where did you get the metal?

Nancy

I'm pretty sure you're not going to accept an answer like I bought it online.

Okay, I think I see where you want me to go next. Metals get mined from within the Earth.

Aunt Alice

Remember that when a potential habitat is first forming as a molten sphere, the denser materials sink down toward the center of the sphere. Metals are relatively dense.

Aunt Peg

No creature with nothing but stone tools is going to dig hundreds of miles down under the surface of their habitat to mine metal.

Aunt Alice

But vulcanism brings metal back up to the surface, or at least much closer to the surface -- within reach, like in caves left behind after lava flowed from deep underground and formed tubes of cooled lava rock. Then, using those easiest to reach sources of metals, tools can be manufactured to explore farther beneath the surface for more materials that are needed to develop technologically.

Aunt Peg

Without vulcanism to create dry land and bring large metal deposits near the surface, there can be no technologically advanced civilization.

Nancy

So, without vulcanism, we would have no dry land and no access to metals.

All together, now, for simplest forms of life to evolve into creatures capable of developing technology, there needs to be a habitat with liquid water and a proper atmosphere and dry land and metals readily available.

Got it. More needs?

Aunt Peg

Oh, yeah.

Back up a bit. Too much vulcanism can cause massive extinctions of species, setting back evolution, maybe even ending any chance of technologically advanced civilizations ever coming to be there.

Nancy

So vulcanism used to be our friend a long time ago; but, nowadays, not as much.

Need adequately stable, moderate climate

Aunt Alice

We are just about to get to that topic of extinctions.

Yes, additional factors have to fall into place just right. Consider climate. The climate needs to be relatively stable. Wild swings in climate would severely damage or

wipe out the natural food chain. When the climate changed drastically and suddenly in the past on Earth, it was the most advanced species, especially the predators at the top of the food chain, which were most in danger of going extinct.

If the climate does not vary too quickly, though, life can adapt to the changes, perhaps by migrating in the near term and evolving over the longer term.

Aunt Peg

Migrating works only if there is always some acceptable climate area to migrate to and only if an adequate assortment of species can physically migrate together to keep the chain of evolution going. Migrating does no good if the critters or plants which the migrating creatures eat don't migrate with them.

Drastic climate changes caused mass extinctions on our planet in the past. For example, when a huge asteroid slammed into Earth about 66 million years ago, the immediate effects on life on our planet were horrendous -- shock wave, tsunami, widespread fire -- but the mass extinction of dinosaurs along with the vast majority of all other species on our planet at that time was due to the resulting change in climate. So much material was thrust into the upper atmosphere by the collision that the Sun's light reaching the surface of Earth was mostly blocked out for many years.

Vegetation died off. The food chain broke down all around the world. Not enough food for small critters to eat meant not enough of the small critters for larger critters to eat, and so forth. As the Sun-blocking material in the upper atmosphere eventually fell back to the surface, the creatures and plants of the small fraction of species which survived began repopulating and diversifying again. But species which were dominant before that asteroid struck were extinct by then, such as the dinosaurs.

Aunt Alice

Then again, it was only after that extinction of those dominant dinosaur species that our distant mammalian ancestors began to flourish and eventually led to us and our technologically advanced civilization. Maybe major extinctions are just what the doctor ordered.

Aunt Peg

Hominids -- our more direct ancestors -- came to be dominant in a world of predators who were almost as scary as dinosaurs, like big cats and bears, and those ancestors hunted giant mammoths. How do we know that mammals would not have still evolved to become the dominant species even in the presence of dinosaurs?

Nancy

Because there have been many movies showing people shooting guns and tanks and rocket launchers at dinosaurs and other monsters which survived from prehistoric times, like Godzilla and Rodan. None of that had any effect on them.

Aunt Alice

You're kidding, right?

Nancy

Of course. Aunt Alice, you have to learn to appreciate sarcasm like Aunt Peg and I do.

Are humans going to become extinct from another huge asteroid colliding with Earth?

Aunt Alice

Not likely. There are telescopes watching the night skies trying to provide years of advance warning of such an impending collision. If humans are not able to deflect a large asteroid or comet in advance of a collision, some humans would still survive the devastation in fallout shelters which were built by the major nations for their national leaders in case of all-out nuclear war.

Aunt Peg

Saving only our political leaders would be worse than our species going extinct. Yes, I am being sarcastic; but you gotta admit there's some truth to that statement.

I agree that our species would survive -- barely -- if a mountain-size asteroid were to collide with Earth now that we have the technology for a small number of humans to survive such a catastrophe. But it was not that long ago, relatively speaking, that our species was almost wiped out by a different event. Alice, do you have any details in your class notes about when Toba blew up? I don't recall what I learned about that catastrophe very well.

Aunt Alice

Yes, I do.

Some seventy-thousand years ago, the Toba super volcano in today's Indonesia blew up and filled the atmosphere worldwide with poisonous gases and particulate matter which prevented much sunlight from reaching the ground -- similar but not as devastating as the effect from the asteroid collision which wiped out the dinosaurs. Still, our distant ancestors, all the hominid species, were almost completely wiped out. The consensus is that the hominid population worldwide dwindled to roughly ten thousand before the condition dissipated.

Aunt Peg

Each mass extinction could potentially undo hundreds of millions of years of evolution; and, if they happen frequently enough, advanced species would never have enough time to evolve and develop technology to survive such drastic climate change. If the Toba explosion had wiped out the rest of our ancestors, we would not be here today.

Nancy

We would have been a technologically advanced species which evolved from cockroaches after all the hominids died out, because everyone knows you can't get rid of cockroaches.

Aunt Alice

I wonder whether that assertion was the product of another dystopian movie you watched.

Aunt Peg

Or maybe she read Kafka.

Nancy

What's a kafka? Sounds like something you eat at an international food fair.

Aunt Peg

Look him up, my dear.

The Toba super volcano came about from the same plate tectonics and vulcanism we spoke about before. There is a need for a balance in the effects of plate tectonics and vulcanism to produce dry land and move metals near the surface yet not change the climate drastically too often. Are you sensing why advanced life on Earth might be unique in our galaxy?

Aunt Alice

To reiterate, though, most species survived those tectonic-driven, climate-changing events in the past which were not as catastrophic Toba. The tectonic plate carrying what is today the Indian subcontinent collided with the Eurasian plate, building up the Himalaya Mountain Range over many millions of years, which led to the annual pattern of monsoon rains in Southern Asia. The creation of the Isthmus of Panama resulted from plate tectonics over millions of years, which halted prior oceanic currents circumnavigating the planet anywhere but near the poles. These gradual changes enhanced

life in some areas and encumbered it elsewhere, always putting pressure on life to evolve.

Aunt Peg

Yes; but again, provided there is at least some region of the habitat with an adequately moderate climate. If the climate in today's Antarctica had always been the most moderate climate on our planet, there would be no humans on Earth. If the climate in today's Death Valley had always been the most moderate climate on our planet, there would be no humans on Earth. That's probably true for any other technologically advanced species, too.

Aunt Alice

Some form of life could exist in such extreme environments, as evinced by there being life forms in both Antarctica and Death Valley. But I agree it is difficult to imagine advanced civilizations evolving in any habitat without some significant area with a moderate climate for a very long period of time.

Need almost circular orbit for stable climate

Nancy

Then how do you avoid extreme climates taking over entire potential habitats?

Aunt Alice

What gives Earth an adequately moderate climate over most of its surface today?

Nancy

There you go again, turning my question back on me.

Aunt Alice

Think about the orbit of the Earth around the Sun. Earth's orbit around the Sun is almost exactly circular. The distance between the Earth and the Sun doesn't vary much as the Earth orbits the Sun over the course of each year.

If our orbit were much more elongated in one direction, which we call a highly elliptical orbit, there would be a greater difference in the amount of heat we derive from the Sun when our orbit would bring us closest to the Sun compared to when we were

farthest away. The more elliptical a potential habitat's orbit would be relative to its star, the more difficult it would be for higher forms of life to survive.

But how circular would a potential habitat's orbit have to be?

Nancy

I don't know.

Aunt Alice

That is the correct answer, because neither does anyone else know. We've only seen one case of evolution of species, that being on our own planet. And in that one case, here on Earth, our orbit around our star is almost circular and has remained that way because other planets in our solar system or massive objects passing by have not come close enough to Earth to drastically upset our orbit with their gravitational attractions. We don't yet know how elliptical an orbit of a planet can be around its star and still allow for advanced life forms to evolve.

This will be one of the many considerations as we later estimate the number of technologically advanced civilizations which might exist in our galaxy.

Need relatively stable rotation axis for stable climate

Aunt Peg

How about a potential habitat's rotation axis orientation?

The rotation axis is an imaginary line through a rotating object around which the object rotates. For Earth, that line would be approximately a line connecting the North and South Poles of our planet. That axis needs to remain rather stable because the orientation of the axis can drive climate change if it isn't.

Aunt Alice

Let's back up a bit to better understand that concept. Nancy, when it's summer in the northern hemisphere of Earth, is the Earth in the part of its orbit closest to the Sun?

Nancy

That question is too obvious because the closer to a source of heat the warmer it feels, so I'm guessing this is a trick question. I'll say no.

Aunt Peg

Good deduction, Sherlock.

Earth is actually in the part of its orbit slightly farther from the Sun while there is summer in the northern hemisphere. But, again because the Earth's orbit is almost exactly circular, that difference between our planet's closest and farthest distance from the Sun is not the major driver in determining the differences among our seasons.

Aunt Alice

What Aunt Peg said a little earlier implies that the major driver is the orientation of the Earth's axis. Why might that be?

Nancy

May I buy a hint, please?

Aunt Alice

You have a globe of Earth in your classroom, right? Picture the globe, which is (or should be) mounted such that its axis is tilted by about twenty-three degrees off vertical, right? Now imagine that globe orbiting around the Sun in the middle of the room. The tricky part is to realize that the axis always stays in the same orientation no matter where the Earth is at any given point in its orbit around the Sun. If that globe you're imagining is tilted toward the desk in front of the classroom, for instance, it is always tilted toward the desk as you imagine it moving around the Sun in the middle of the room.

Nancy

I can see that the top half of the globe -- the northern hemisphere -- is closer to the imaginary Sun in the middle of the room when the globe is in the back of the room and the southern hemisphere is closer while the globe is in the front of the room. But that's a tiny difference. That has to be less than the difference Aunt Peg just dismissed based on the Earth's orbit around the Sun not being exactly circular.

Aunt Alice

Indeed, yes, that is a tiny difference. But think about how the Sun's rays fall on the northern hemisphere differently as the Earth orbits it. In one half of the Earth's orbit, the Sun's rays fall on the northern hemisphere more straight on -- more from directly overhead; while the southern hemisphere gets the more direct illumination during the other half of the orbit. Think about how much warmer sunlight feels when the Sun is closest to being overhead -- around noontime -- compared to early morning or late in the day.

Nancy

Is that also why the Sun is higher in the sky in the summer than in the winter?

Aunt Peg

You got it. Another good deduction, Sherlock.

Getting back to the point, the orientation of the Earth's axis is tipped close to twenty-three degrees off vertical and it varies slowly over tens of thousands of years by only plus or minus one degree or so. That amount of variation and rate of variation has not played havoc with our planet's climate and evolution of life.

If, however, it were wobbling significantly more than that and especially if it did so much more rapidly, all of the surface of the Earth would likewise experience greater and faster climate change as a direct result. If that were the case, think about what would happen to vegetation and other life forms at the bottom of the food chain on our planet.

Stabilizing a rotation axis orientation requires having a relatively large moon orbiting around the planet whose steady gravitational attraction inhibits the axis of the planet from wobbling. Earth is the only planet in our solar system with such a moon.

Nancy

Why is that?

Aunt Alice

The most commonly held explanation is that our Moon resulted from a collision during the early formation of our solar system.

We talked previously about how a massive cloud coalesces into a star and its solar system. The mass of cloud which does not coalesce into a star at the center starts clumping together into larger and larger "blobs" orbiting around the central star.

The bigger the blobs get, the more their gravitational attraction. The more their gravitational attraction, the more they accrete stuff from the cloud. As the blobs grow, they also crash into each other. The explosion from such collisions disperses some of the already-accreted mass of the colliding blobs initially, but the mutual gravitational attraction of all the mass gradually causes most of the mass of the colliding blobs to reform into a single, even larger blob.

Some blobs eventually grow big enough to clear out all other comparably large blobs near their orbit. Those become the planets in our solar system. Some smaller blobs which don't collide with early planets can get captured by the gravity of a planet and become the planet's moons.

Aunt Peg

The consensus is that our Moon was not captured. Analysis of the composition of the Moon together with computer simulations strongly suggest our Moon formed when

early Earth and another almost-as-large blob collided in a glancing blow relatively late in the process of planet accretion. So much mass was initially dispersed from that collision that the mutual attraction of some of the dispersed mass was able to coalesce into the Moon and continue orbiting around the early Earth, instead of all falling back onto the early Earth.

If that is correct, it was a freakish occurrence. Had the collision occurred significantly later when Earth was larger, the greater gravitational attraction of early Earth might have sucked back more -- or even all -- of the mass which coalesced into our Moon. Or, if it occurred when Earth was significantly smaller, too little gravitational attraction might have allowed much of today's Moon to escape, instead. If the glancing blow of the collision had been appreciably different as to direction of approach or how far off-center the two collided, the results would have been very different, too.

If we did not have such a relatively large moon and our planet’s axis therefore wobbled much more and much faster than it does, would a food chain ever have been established which was stable enough such that a technologically advanced civilization would have evolved on our planet?

Aunt Alice

Let’s imagine our Moon is much smaller than it is and therefore the Earth’s rotation axis orientation varies by more than the total couple of degrees of angle that it does now. How much and how fast could those variations have been before those variations would have prevented humans from evolving here on Earth?

Consider how quickly climate is changing on Earth today due to the greenhouse gasses accumulating in our atmosphere. Even as fast as that is happening already, and even as fast as it is expected to change over the rest of this century, humans are not going to become extinct as a result.

Aunt Peg

As the greenhouse effect drives sea level higher because of ice melting on Greenland, Antarctica, and elsewhere, hundreds of millions of humans currently living near sea level are going to be displaced. Many others will flee from severe droughts which will transform formerly arable land into deserts, or from areas becoming routinely inundated by flooding, or from places becoming too hot to survive for much of the year.

If you think the recent surge of anti-immigrant reaction around the globe is bad now, wait until you see the wars and genocides when hundreds of millions of people need to migrate.

Aunt Alice

I won’t deny we are going to face increasingly difficult pressures and catastrophes due to our currently changing climate. Eventually, I hope and expect we will be

forced to work together to put a stop to what we have been doing and find ways to deal with it and perhaps even reverse what we've done.

Aunt Peg

I, too, hope that will happen, and the sooner the better. I'm just less confident than you. When you mess with Nature, Nature exacts revenge.

Aunt Alice

Again, getting back to the point here, as the Earth's rotation axis orientation changed its angle slowly over tens of thousands of years, areas on Earth where the climate was congenial were in different locations, but life adapted gradually. We don't know how large a moon would have to be relative to its planet to adequately stabilize the potential habitat's rotation axis orientation nor how likely it would be for a potential habitat to have such a moon.

I'll admit, though, it is a consideration, to some unknown extent.

Aunt Peg

Nancy, I'm going to agree with your Aunt Alice on this one. Let's not keep the need for a relatively stable axis on the list with the need for an almost circular, stable orbit around a star. An axis changing orientation is not as compelling of a need in order for a habitat to have adequately moderate climate.

Nancy

I wish the rest of the world's disagreements were discussed as rationally.

Need to avoid tidal locking to the star for moderate climate

Aunt Alice

The next thing from my course notes to consider is tidal locking.

Nancy

Tidal locking? As in locking away the tides?

Aunt Alice

Sarcasm again?

Nancy

No, seriously, I haven't a clue what that means.

Aunt Alice

We were discussing the need for areas of moderate climate on a potential habitat. What role in determining climate does the rotation of a potential habitat play?

Nancy

You mean like the Earth rotating on its axis while it orbits around the Sun?

Aunt Peg

Precisely. Think about how the radiated heat from the Sun gets distributed over the Earth.

Nancy

As the Earth rotates once each day, the Sun heats that part of the Earth's surface facing it each moment, while the Earth's rotation continually changes the part which faces the Sun. It's as if the Earth were on a spit in a rotisserie oven in front of the broiler.

That was an analogy. I get extra credit for that.

Aunt Peg

Since neither of your aunts are fortunate enough to have you as a pupil (yet?), you'll have to settle for a pat on the head for now.

You are correct. A star's radiated energy is distributed around a planet or moon largely by the planet or moon moving such that the star's radiation shines progressively on ever-changing parts of the surface. However, if a potential habitat's rotation and orbit match each other so that the same half of the habitat always faces its star while the other half never does, we refer to that phenomenon as "tidal locking."

Nancy

That seems like it would be very unlikely to happen.

Aunt Alice

Not at all. Tidal locking routinely occurs when an object in space is so close to the object it is orbiting that the mutual gravitational attraction between the two causes the orbiting object's rotation to slow until it matches the object's orbital rate.

For example, our Moon is tidally locked to Earth. The Moon rotates once on its axis during the time it takes to complete one orbit around the Earth. The Moon's rotation therefore keeps the same side of the Moon facing the Earth, always. That is the only side we can see from the Earth. The other side, often referred to as "the far side of the Moon," was never seen by any human until a spacecraft orbited the Moon taking pictures of that other side.

Aunt Peg

While the Moon offers an example of tidal locking, the significance of tidal locking to our discussion is that it also happens when a planet orbits very close to its star, too. When that happens, the surface of the planet would be too hot on the side always facing its star and too cold on the other side for the evolution of technologically advanced life.

Aunt Alice

I recall briefly seeing a headline somewhere saying some folks at SETI did simulations or calculations which they believe suggested there might still be moderate climate areas on a planet tidally locked to its star. The concept is that radiated heat from the planet's star can also be distributed around the planet via convection: an atmosphere and ocean absorbing the heat on the side facing its star, then moving around the planet, depositing some of that heat to the dark side of the planet. That would lessen the two extremes, maybe even leading to areas of moderate climate, at least near the dividing line between the star-facing side and the dark side.

Aunt Peg

If the planet has an atmosphere and oceans that could theoretically circumnavigate the planet, wouldn't they both become too cold on the dark side to allow planet-wide convection? Wouldn't any liquid water on the cold, dark side freeze and the liquid water on the hot side boil, rather than establish strong currents to bring heat from the hot side to the cold side? The atmosphere on the cold side would get so cold, wouldn't it start to turn into liquid itself? Eventually, wouldn't almost all the atmosphere become a pool of liquid on the cold, dark side as more and more of the atmosphere which ventures into the dark side gets liquified?

And if the atmosphere doesn't liquify, can you imagine the winds that would blow constantly across the dividing line between the hot side and the cold side because of having such a difference in heating from the star between the two sides? That wouldn't result in a moderate climate near the dividing line between the two sides.

Aunt Alice

I'll try to learn more about that claim for convection on a tidally-locked potential habitat allowing for areas of moderate climate. If it turns out to be very plausible, that would have a significant impact when we estimate how many habitats there might be in our galaxy where technologically advanced alien civilizations could potentially have evolved. In the meantime, I have to admit your points seem compelling. Let's just keep the need to avoid tidal locking of a potential habitat to its star as one of our criteria for our discussion today.

How many potential habitats might there be which meet the criteria?

Nancy

Good. Now we start estimating how many alien civilizations there might be in our galaxy. Right?

Aunt Peg

Yeah, Alice, are we there yet? Are we there yet?

Aunt Alice

Alright you two.

Let's start by trying to estimate the number of potentially viable habitats in our galaxy and whittle it down from there based on all the specific needs we discussed.

How many stars might have potential habitats?

Aunt Peg

We can rule out any part of the galaxy where a potential habitat would likely be sterilized repeatedly.

Nancy

Sterilized? Sterilized by what?

Aunt Peg

Exploding stars -- especially supernovas -- and pulsar neutron stars and black holes and whatever other source of intense radiation and high energy particles might be too nearby the potential habitat so that every life form on and near its surface, as well as all the ingredients on the habitat needed for advanced life to evolve and survive get blown away or incinerated or even just irreparably disrupted.

Nancy

That happens out there? The real universe is sounding more dystopian than dystopian movies.

Aunt Alice

Exploding stars are relatively rare events, and neutron stars and black holes are likewise relatively rarely found in the galaxy. However, they're out there, and it's not good for life to be close by, as your Aunt Peg overly-dramatically stated.

Nancy

Are we too close?

Aunt Peg

Not for the past four billion years or so, apparently. While there is evidence that radiation and streams of high energy particles from these menaces have impinged on Earth in the past, none of those sources were close enough to end all life on our planet, obviously. However, there are some who believe such an incident might have been the reason for at least one mass extinction in the distant past. We are not aware, though, of any nearby stars which are likely to pose a major threat to us over the next million years, at least. The main reason for that good fortune is that we are not near a lot of stars presently.

Had our solar system been located in a part of our galaxy where stars are more densely packed, that would have increased the chances that Earth would have been sterilized in the past -- and the future. If it typically takes as long as it did on Earth for advanced technology to evolve on other potential habitats, a sterilizing event once every billion years or so, on average, could easily preclude any technologically advanced civilization.

We need to rule out all the parts of our galaxy where stars are packed together densely.

Nancy

What causes stars to explode?

Aunt Peg

Let's digress briefly and talk about the life cycle of stars. Understanding the basics of stars will help a lot as we proceed.

Aunt Alice

To understand what Aunt Peg is asserting, we need to first talk a little about how stars are born, live, and die; based on what astronomers observe in the sky and from our understanding of physics and chemistry.

Between thirteen and fourteen billion years ago, the early universe had no galaxies or stars. It contained, though, an incredibly large amount of hydrogen plus a little (relatively speaking) helium and even less lithium. Those are the three lightest elements, in order, hydrogen being the lightest.

Aunt Peg

And probably also other stuff we call "dark matter." We call it that because we have not yet been able to figure out what it is.

Gravitational attraction comes from mass. There appears to be more gravity in the universe than can be accounted for by all the stuff with mass which we know about. Therefore, we conclude there must be more mass in the universe than what we have identified and, at least for now, until someone figures out what comprises all that additional mass, we refer to the currently unidentified mass as dark matter.

Aunt Alice

The distribution of everything out there in the early universe wasn't exactly uniform. Where the mass of stuff was more dense, some of the stuff started to collapse, drawn together by mutual gravitational attraction. Gradually, the stuff in the early universe coalesced into clumps of stuff from which were formed our first galaxies.

The clumps did not all simply continue to collapse because they started to spin as they began to collapse. The mutual gravitational attraction among everything in the clump typically prevented all the stuff from falling in a straight line toward some central point within the clump. Certainly, a lot did come together in what became the center of a galaxy; but huge amounts ended up orbiting around that center, even out to very large distances from the center.

For example, the distance from the center of our galaxy to what one could consider the outer edge is something like nine-hundred-thousand-trillion miles, and we determined there are galaxies in the universe larger than ours. Nine-hundred-thousand-trillion is a number too big to fathom.

In astronomy, we keep having to deal with numbers which are so large that humans simply can't get a feel for what they mean. It's not a coincidence that numbers like nine-hundred-thousand-trillion miles are referred to as being "astronomically large."

Nancy

How long would it take to travel across our galaxy?

Aunt Peg

The fastest velocity in the universe, as far as anyone knows, is the speed which light travels in a vacuum, such as in space. At the speed of light, it would take roughly 150,000 years to go across the entire Milky Way galaxy, starting from one farthest outer extent of the disk, right through the center, and out to the opposite farthest extent. At the fastest speed which any human-made spacecraft has yet traveled, it would take well over half a billion years to travel that distance.

Aunt Alice

Within the clumps which became galaxies, denser regions likewise started to collapse into the earliest stars due to mutual gravitational attraction of the stuff in those denser regions. When enough mass coalesces together that the density and temperature in the core of the star reaches a critical point, hydrogen atoms in the core start to fuse together into helium atoms. We talked about that earlier.

Each such fusion gives off lots of energy. This energy from a steady stream of fusions eventually makes its way to the surface of the star and emanates out in all directions in various forms. That portion of the emanating energy in what we call the “visible part of the spectrum” is what we see with our eyes as the light coming from the star.

Meanwhile, the energy from fusing hydrogen into helium also pushes against the outer layers of mass in the star preventing the star from collapsing further onto its core.

Aunt Peg

Astronomers with our telescopes staring into our galaxy can see stars forming, stars shining, and the remnants from when stars exploded.

We’ve come to understand that the life cycle of stars depends on how large was the mass of the stuff -- mostly hydrogen -- which originally coalesced into the formation of the star. That determines how fast a star emanates energy (that is to say, it’s output power), how long the star emanates energy, and what kind of changes the star ultimately undergoes.

Aunt Alice

Eventually, almost all of the hydrogen in the star’s core gets converted to helium, then the rate at which the star produces energy falls off, and it starts to collapse again.

If the star is massive enough, it will reach another critical point as it collapses further when the density and temperature in the layers just outside the core become great

enough for fusion of hydrogen into helium to begin there, anew. This again stalls further collapse of the star and it continues to produce and emanate energy from fusion.

If it is massive enough, the core of the star would eventually become dense enough and hot enough that the helium in the core will begin to fuse into heavier elements, producing and emanating more energy.

The most massive stars can go through successive stages like this, fusing lighter elements into heavier and then still heavier elements, until their cores have created too much iron. Iron is so stable that it requires more energy to force iron to fuse into heavier elements than is derived as a result of that fusion. Therefore, eventually, a massive star's core is left with not enough fuel to allow it to continue producing enough energy fast enough to keep its outer layers from collapsing any longer.

At whatever point a star runs out of the ability to counteract the force of its own gravity, its gravity will cause the star to collapse on itself. The collapse results in a tremendous explosion, shooting some of the star's mass out into space at very high speeds.

After medium-sized stars eventually explode, they leave behind very dim remnants which we call "White Dwarf" stars. Larger stars leave behind what we call "Neutron Stars." The largest stars leave behind what we call "Black Holes."

Aunt Peg

A Neutron Star is so dense that the equivalent of a spoonful of it would have as much mass as a mountain.

A Black Hole is even more dense than a Neutron Star. It is the densest form of matter we know of. This remaining remnant from the largest stars -- after they explode in what we call a "supernova" -- compacts into something so dense that the gravitational attraction it exerts captures anything which gets too close. Even light from a star which passes near it can't escape being pulled into it. It's like a hole in the universe. Although, when stuff begins to get sucked into a black hole, powerful X-ray and other radiation gets emitted.

Aunt Alice

Both neutron stars and black holes can send out intense beams of energy which can be exceptionally destructive. Their destructiveness diminishes the farther away you are from them.

Nancy

What will our Sun become?

Aunt Alice

Our Sun is a medium-sized star, so it is expected to eventually collapse into a White Dwarf star.

Aunt Peg

But before our Sun collapses into a White Dwarf, it is expected to first expand into what we call a “Red Giant.” A Red Giant star is much larger in size than the star from which it came and the surface of a Red Giant is still very hot. Eventually, it will collapse further into a White Dwarf star which will then cool over billions of years and get dimmer and dimmer with time.

Nancy

When will it expand into a Red Giant?

Aunt Peg

Roughly five billion years from now.

At that time, the surface of our Sun will grow out into our solar system and engulf the first two planets from the Sun: Mercury and Venus. It’s questionable whether it will grow big enough to engulf its third planet, which is our Earth. However, even if it doesn’t quite get that large, its hot surface will be so close to Earth that it will boil away our atmosphere and our water and make the surface of Earth uninhabitable.

Like I said, though, that’s a few billion years away. You’ve got a little time before you need to start worrying about it.

Nancy

Yeah, but still, it seems kind of scary, don’t you think?

You called our Sun a medium-sized star. So are there smaller stars?

Aunt Alice

Yes, there are stars called “Red Dwarfs,” which brings up an interesting question. Which stars would you expect to shine the longest before exploding, the most massive ones or the smaller ones?

Nancy

The most massive stars have the most fuel to burn and they extend their lives longer by fusing heavier and heavier elements. So they would shine longest.

Aunt Peg

That seems obvious, right? Except the correct answer is exactly the opposite. For larger and larger stars, despite there being more fuel to burn, the rate at which the more massive stars burn through their fuel increases faster than the mass of the star increases. Counterintuitively, the more massive the star, the faster it burns out and explodes.

The expected lifespan of stars like our Sun is roughly ten billion years before exploding. The most massive stars might shine as little as about a hundred million years before going supernova. The smaller Red Dwarf stars burn their fuel so slowly that they are expected to last for perhaps trillions of years. The universe being less than fourteen billion years old, none of the Red Dwarf stars in our universe have burnt out yet.

Aunt Alice

Another perhaps counterintuitive result is that the explosion of a star can give rise to other stars forming. While some stars form relatively quickly from the cloud of stuff in an early galaxy, the stars don't all form at the same time throughout the galaxy. Most of the cloud in the galaxy remains nothing more than a cloud, until something happens to disturb it in a major way. In particular, if a nearby star explodes, it generates a powerful shockwave of highly energetic particles and atoms and intense radiation propagating through space.

Aunt Peg

If you put your finger in a bowl of water and move your finger across the bowl you see little swirling eddies -- small whirlpools -- form behind your finger's motion across the bowl. The shock wave from an exploding star can have a similar effect when it passes through a cloud in the galaxy.

Each of the resulting eddies is a piece of the cloud which then starts to swirl and collapse under its own gravitational attraction. Most of the mass within each whirlpool coalesces into the center of the swirl and, if there is enough mass at that center, eventually becomes dense enough for nuclear fusion to begin there. Then, like I said earlier, a star is born.

Aunt Alice

In order to rule out the too-densely packed parts of our galaxy, as Aunt Peg urged us to do, we need to picture what our galaxy looks like.

Most of the stars in our galaxy lie in a relatively flat disk, except with a bulge of stars in the middle. Within the disk, most of the stars are located in four spiral arms emanating away from that central bulge. When we look at our galaxy from our vantage point here on Earth, we can't distinguish the spiral arms. The light from the stars in the spiral arms blend together into thin streaks on either side of the bigger bulge of stars in the center. It's like looking at a frisbee from its edge. You can't really see the actual disk of the frisbee unless you could see it from above.

We also see dark blotches when we look at our galaxy. That's because there are clouds of stuff -- mostly hydrogen -- floating around inside our galaxy which absorb visible starlight trying to pass through those clouds. Whenever a cloud gets between a star and us, the light from that star which our eyes could normally see doesn't make it to our eyes.

Our solar system is currently located near the edge of one of those spiral arms. So we are not near a lot of other stars. The closest star is Proxima Centauri, twenty-five-trillion miles away. It takes four and a quarter years for light to reach us from that star.

Aunt Peg

Getting back to the central bulge of our galaxy now, the stars there are much more densely packed together than elsewhere in the galaxy. It seems extremely unlikely advanced life forms could have evolved there in between nearby star explosions and other sources of intense radiation.

Aunt Alice

I agree for the most part, with a little bit of hesitation, though.

The greater density of hydrogen near the center of the early galaxy made it more likely that the stars which formed within the central bulge were not just more closely packed together but also more likely to be massive stars. Between the relatively quickly exploding massive stars with their deadly radiation coming from many of the remnants of exploded stars, the central bulge became a killing zone relatively early on.

But our galaxy is approaching fourteen billion years old. With all those massive stars exploding quickly in the early timeframe of our galaxy, leaving many billions of years for things to become less dangerous, there would have been plenty of time for life to start again and evolve.

Aunt Peg

That's only if life can start again after such a sterilization as a nearby supernova explosion would cause.

But even if things calmed down dramatically in the center of our galaxy and even if life could start anew, there is still the danger from stars and massive star remnants being so close to each other that their strong gravitational influences would mess up each other's orbits and the orbits of each other's planets and moons. If we maintain any hope for technically-advanced civilizations in the central bulge for now, we're only going to rule out all potential habitats there for not meeting the criteria of climate stability when we get to that later.

Aunt Alice

Recent estimates I've seen claim less than one percent of the stars in our galaxy are in the central bulge. Plus or minus one percent is not going to matter when we start trying to come up with numbers. So, sure; let's rule out the central bulge, as you recommend.

Aunt Peg

What about ruling out the densest parts of the spiral arms of the galaxy for the same reasons?

Aunt Alice

I disagree with you on that recommendation.

Our solar system has not always been located outside a spiral arm of the galaxy. Instead, it orbits the center of our galaxy, moving through the spiral arms as it orbits, taking some 250 million years to complete an orbit of the galaxy. In the process, it traverses one spiral arm after another, typically taking ten million years for each traversal before heading toward the next spiral arm. That's a lot of time spent inside spiral arms and evolution has managed to proceed despite those traversals.

Clearly, the spiral arms are more dense with stars and star remnants than in between the arms, as you said. However, if Earth traversed the interior of those arms multiple times, spending millions of years traversing each, and that hasn't precluded our evolution, I think it is too much of a generalization to preclude potential habitats currently within the spiral arms.

Aunt Peg

Okay, I'll agree with that.

Next, how about the star systems in the outer reaches of our galaxy which almost entirely don't yet have the heavier elements required for life to exist?

Aunt Alice

Yes, we need to rule those out, too.

Nancy

Why are there no heavier elements out there?

Aunt Peg

Remember when we talked about the evolution of stars a little while ago? Heavier elements, which include oxygen, carbon, phosphorous, iron, etc., many of which are required for life to exist, are all spewed out into the galaxy when massive stars burn out

quickly and explode. Those heavier elements eventually move out into the rest of the galaxy and become part of the clouds from which new stars with their solar systems will later form.

In general, the earliest, massive stars formed near the center of the galaxy because that was where the clouds were the most dense. Therefore, most of the creation by fusion in massive stars of heavier elements began near the center and the heavier elements were gradually distributed farther and farther out from the center as heavier elements were incorporated in younger solar systems whose stars eventually also exploded.

Measurements of the light coming from stars in the outer reaches of our galaxy show little of the heavier elements have yet made it out there. Too little heavier elements means life would be non-existent in those outer reaches of our galaxy.

Aunt Alice

Alright, ye of great skepticism. After ruling out the core of the galaxy and the relatively sparsely populated outer fringes of the galaxy, how many stars do we have left to consider? Most of the estimates I've seen claim there are roughly 200 billion stars in our galaxy. Can we start with a round number like 100 billion after ruling out the core and fringes?

Aunt Peg

Sure. We'll start with 100 billion stars in our galaxy to consider. Next we need to rule out categories of stars within that 100 billion.

Massive stars burn out and explode far too quickly. A potential habitat in the early solar system of a massive star would not even have enough time to cool from its molten phase before the massive star would explode.

Rule out stars in the Red Giant phase. The Red Giant phase of a medium-sized star's evolution lasts roughly a billion years. If any advanced life forms had evolved in the former star's Goldilocks Zone before the star ballooned into a Red Giant, they're not living there anymore. Also, advanced life wouldn't have enough time to evolve from scratch before the Red Giant would collapse into a White Dwarf, too dim to support a plausible Goldilocks Zone.

Aunt Alice

Slow down, please.

Massive stars are out? -- sure.

Red Giants are out? -- I'm not so sure. If a technologically advanced civilization existed in a solar system of a star like ours before it became a Red Giant, and those aliens realized that change was coming -- like we do -- couldn't they survive the transition

by moving their lives underground, if their technology was somewhat better than ours is today?

Aunt Peg

Would they have the ability to survive that long against such conditions but not have the ability to move their civilization to another planet or moon, or even another solar system?

Aunt Alice

I suspect the challenge of moving their civilization off their home habitat would be significantly greater than moving underground.

Well, the fraction of stars in our galaxy in the relatively brief Red Giant phase is not worth fretting about for our purposes here. Let's rule out Red Giant stars, as you recommended.

We'll return to this question about surviving a catastrophe when we talk about rogue planets in a little while.

Nancy

Rogue planets??? I love the sound of that. I can't wait to hear this story.

Aunt Peg

Nancy, you seem to have an interesting attraction for the bizarre.

Alice, what did you learn about binary stars when you prepared to teach your Natural Science for Poets course? Should we rule them out?

Aunt Alice

Surprisingly, I recommend we should not rule them out.

Nancy

Uhh, hello. Binary stars?

Aunt Peg

There is a high likelihood that some stars, especially in the denser parts of the galaxy, formed close enough to each other and with enough mass that they orbit a location in space between them. There have even been observations of more than two stars locked together in this kind of a dance.

Aunt Alice

Based on observations, the latest thinking I've read is that roughly a third of the stars in our galaxy are in multi-star systems, mostly binaries.

We've already found planets orbiting a binary star pair in which the two stars are close to each other. It is as if the pair is acting like a single star and share a solar system orbiting around the pair.

If, instead, the stars in a multi-star system keep far enough apart from each other while they revolve around each other, then the gravitational influence of one star on the objects in the other star's solar system could be negligible relative to the star's own gravitational attractive force on the objects in its own solar system.

Aunt Peg

How about Red Dwarf stars? On the one hand, you might think they would be great candidates for finding technologically advanced civilizations because those stars can last for a trillion years or more -- plenty of time for life to evolve. However, just like larger stars, Red Dwarfs have solar winds of highly-energetic, charged particles emanating from their surfaces.

As we discussed previously, solar winds can play havoc with atmospheres and life forms. Red Dwarf stars are relatively dim, so potential habitats orbiting a Red Dwarf in the Goldilocks Zone of that Red Dwarf would be relatively close to their star. The closer a potential habitat is located to the source of a solar wind, the more intense would be the impinging highly-energetic particles because they would not have spread out as much compared to having traveled farther before arriving at the potential habitat.

There's another problem with Red Dwarf stars. Again, because potential habitats within the Goldilocks Zone of a Red Dwarf are so close to their star, they will likely be tidally locked to their star. When we discussed tidal locking before, we decided that needed to be avoided.

Aunt Alice

The planets within the Goldilocks Zone of a Red Dwarf could be ruled out due to tidal locking, but what about a moon of one of those planets. As the moon orbits its planet, it would show varying parts of its surface to its star even though the planet wouldn't.

Aunt Peg

True, but the moon would likewise be bathed in the intense solar wind. I seriously doubt advanced life could evolve on any potential habitat in the Goldilocks Zone of a Red Dwarf in the presence of such intense bombardment.

Aunt Alice

Despite all that, it is interesting to note that a few years ago the folks at SETI started aiming some of their telescopes at Red Dwarf stars to search for signals from technologically advanced civilizations.

Aunt Peg

Had the SETI folks detected unambiguous evidence of such a civilization at a Red Dwarf, that would have been a very convincing argument here, naturally. As it is, though, since we are debating whether SETI is a wasted effort in general, pointing out what SETI is choosing to do as evidence to justify what they are doing strikes me as circular reasoning.

Aunt Alice

That was just a note of interest. I'll concede on Red Dwarfs. Let's rule them out.

A little while ago, before discussing the categories of stars, we came up with a round number of 100 billion stars in our galaxy worth considering. It is estimated that something like seventy percent of all the stars in our galaxy are Red Dwarfs. If we rule out Red Dwarfs and the billion or so neutron stars and the hundred million or so black holes, we're left with something like thirty billion stars which might harbor potential habitats.

Aunt Peg

... works for me.

Number of potential habitats among those stars

Aunt Alice

Given our estimate of thirty billion medium-sized stars to consider, how many potential habitats might there be out there, on average, for each of those stars?

Our best estimate of that number was improved significantly in recent years because of the Kepler telescope launched into space in 2009 to survey stars, looking for evidence of planets in their solar systems -- so-called "exoplanets." Prior to the Kepler mission, our methods of searching using telescopes on Earth were only sensitive enough to see evidence of very large planets very close to their stars; which we did see. Once the Kepler telescope was working and relaying the images it acquired without the distortions of looking through Earth's atmosphere from the ground, we were able to additionally look for evidence of planets more like Earth; which we saw, too. We hope and expect to learn considerably more about exoplanets in the not-too-distant future as more telescopes are launched into space to search for them.

Estimates I have read most recently based on scientists analyzing the data Kepler sent back are that there might be at least as many planets orbiting stars in our galaxy as there are stars in our galaxy -- something like one planet per star, on average. But that's for all the stars, including Red Dwarfs, which we agreed to rule out for our discussion today; so that estimate is not necessarily true for our roughly thirty billion stars of interest to us in this discussion.

Others have gone further with the Kepler data and tackled a large part of the question we are discussing now. They estimated that there might be approximately ten billion roughly-Earth-size exoplanets orbiting within the Goldilocks Zones of stars similar to our Sun within our galaxy.

Aunt Peg

Are you suggesting we take this ten billion estimate as the number of potential habitats in our galaxy and skip immediately to winnowing them down based on our list of needed criteria?

Aunt Alice

Not quite yet.

That estimate of ten billion rules out planets in their stars' Goldilocks Zones which are much larger than Earth but omits the possibility of moons of those much larger planets being potential habitats. The Kepler mission was not capable of searching for moons.

Aunt Peg

We talked previously about how, as a star forms, it accretes or blows away so much of the cloud nearest itself. Therefore, there is not enough stuff left near a star for a giant planet to form there. We also talked about how planets can form far away from a star but then migrate inward toward the star. Therefore, if there is a giant planet in the Goldilocks Zone of a star, that planet had to form farther out in the solar system and migrate inward.

Also, as previously discussed, while a giant planet migrates slowly into the Goldilocks Zone from farther away, it would interact gravitationally with planets initially orbiting between itself and its star. That would likely perturb the orbits of any smaller planets which were initially inside the Goldilocks Zone -- probably making those smaller planets no longer viable, potential habitats. Even if the giant planet brings one or more Earth-size moons along with it into the Goldilocks Zone, the inward migration of the giant planet could easily make non-viable one or more planets already in the zone. I'm not seeing a likely substantial net increase in the number of potential habitats per star by throwing into the mix moons orbiting giant planets.

Aunt Alice

Not surprisingly, I'm more optimistic than you about a net increase, but I don't dispute the basis of your argument. Let's agree, then, not to increase that prior estimate of roughly ten billion potential habitats by some arbitrary amount.

Aunt Peg

Now are we ready to move on with ten billion potential habitats to whittle down?

Aunt Alice

Almost. One more crazy idea first.

Speaking about how large planets can play havoc with the orbits of smaller planets, I think it is time to get back to Nancy's too-long deferred journey into the realm of rogue planets?

Nancy

Finally!

Aunt Peg

Rogue planets: ominous, sinister, foreboding.

Aunt Alice

Rogue planets are not ominous, sinister, or foreboding. Besides, those are three synonyms saying the same thing.

Aunt Peg

Picture yourself on a planet, let's say Earth. A small black hole comes whizzing through our solar system. Even though it is small, the black hole exerts such a huge gravitational attractive force that it effectively grabs the Earth and flings our planet as if the black hole were a discus thrower and our planet were the discus. The abrupt acceleration in being hurled out of our orbit causes everything not firmly attached to bedrock to go flying asunder. With most of its atmosphere and water flung away irretrievably, Earth heads out of our solar system and into unrelenting cold, dark, empty space. Earth becomes a rogue planet wandering aimlessly in our cruel galaxy -- a planet on which everyone and everything who might have survived the horrible acceleration of the encounter eventually dies in the frozen depth of space.

Aunt Alice

That's my sister: Peg, the weaver of dystopian nightmares.

Nancy

Could it happen?

Aunt Alice

The likelihood of that happening to Earth within the next many thousands of years is nil. The orbits of the planets in our solar system have been extremely stable for a very long time and are expected to remain that way for a very long time. Neither Jupiter nor Saturn are migrating toward us. In addition, there have been no indications of any stars or star remnants getting close enough in the foreseeable future to induce such a catastrophe.

Aunt Peg

Extremely unlikely for us, sure. Yet estimates are that there are at least as many rogue planets in our galaxy, cast out from the solar systems in which they originally coalesced, as there are planets in our galaxy still bound to their original stars. Whether due to giant planets migrating inward or a black hole passing by or another star passing by, planets get tossed out from their solar systems.

Aunt Alice

Some of those rogue “planets” could have also been moons which were originally orbiting planets in their stars’ solar systems before massive objects came close enough to rip those moons away from their planets and hurl them into space.

Besides, any technologically advanced civilization on a planet or moon in a solar system with even just the technology we have here today would be able to see such an event coming a long time in advance. Although black holes cannot be viewed directly because no light can escape from them, their gravitational influence on light passing by them can be viewed. Black holes bend light’s path toward them if light passes by closely but not so close as to be captured by the black hole. Approaching stars would be obvious in our telescopes, as well.

Furthermore, as I said before, I think it is plausible that a technologically advanced civilization might be able to relocate deep underground and survive, meeting their energy requirements by tapping the internal heat of the planet and using whatever fuel they have available -- fossil fuels, nuclear power, fusion power. I think some unknown, probably unknowable number of rogue planets might harbor technologically advanced civilizations.

Aunt Peg

And as I responded before to this idea, I am very skeptical of surviving for eons adrift in space, confined deep underground while any remnants of the prior atmosphere

and oceans not ripped away in the encounter lie frozen solid on an uninhabitable surface.

Nancy

That might be an even worse dystopian nightmare than the encounter which sent the planet adrift into the galaxy.

Aunt Peg

This discussion is ultimately about detecting alien civilizations. What detectable signals would leak out from a civilization deep underneath the surface of their buttoned-up-against-the-cold rogue planet?

Aunt Alice

They could have antennas and telescopes on the surface to watch for potential future approaches of heavenly bodies which they would either need to prepare for or could consider trying to relocate to if hospitable. Perhaps they would use some form of radar, with lasers perhaps, to continually monitor their path. Maybe we could detect such signals.

I know, it's a long shot compared with planets and their moons orbiting their stars. I just wanted to mention the possibility.

Now I'm ready to proceed to whittling down the estimate from Kepler data of around ten billion potential habitats located within Goldilocks Zones of stars similar to our Sun.

Summary of criteria which will be considered

Aunt Peg

Good.

Favorite Niece Nancy, you've been diligently compiling a list of the needs as we discussed them. Would you please read that list back to us?

Nancy

Okay. Let's see.

Need habitat to be in Goldilocks Zone in order to potentially have liquid water on surface. But the ten billion estimate was for potential habitats in Goldilocks Zones. So I guess that criteria is taken care of already. However, need to stay in zone long enough for advanced civilization to evolve.

Need bombardment of water-bearing objects like asteroids and comets to bring water to Goldilocks habitat.

Need adequate atmosphere to keep the water from escaping off into space.

Need adequate gravity to keep atmosphere from floating off into space.

Need adequate magnetic field to keep atmosphere from being blown off into space by solar wind. Also need adequate magnetic field to protect life forms from destructive effects of solar wind.

Need hot interior of habitat driving iron flowing there to create magnetic field.

Need habitat size big enough to avoid interior cooling down and losing magnetic field before advanced civilization can evolve.

Need the bombardment of water to occur after the habitat has enough gravity and magnetic field to keep the water.

Need right amount of oxygen in the atmosphere.

Need right amount of gasses which produce the greenhouse effect.

Need dry land.

Need enough vulcanism and plate tectonics to create dry land and bring metals to surface, but not so much as to continually undo evolution of species toward advanced life forms.

Need moderate, stable climate.

Need to avoid tidal locking to the habitat's star. But you pretty much did away with this criterion when you guys agreed to rule out potential habitats in solar systems of Red Dwarf stars, didn't you?

Aunt Alice

Yes, we can leave out tidal locking as a criterion now. Potential habitats in Goldilocks Zones of solar systems with the type of stars we are still considering are not likely to be tidally locked to their stars.

Excellent. You've been doing a great job of following along and taking notes.

Whittling down number of potential habitats

Nancy

Let the winnowing begin -- well, the next round of winnowing, that is. We've already reduced the number from hundreds of billions to maybe ten billion.

Aunt Alice

Nancy, here is where your two aunts are going to start guessing at different numbers based on our biases about what might be out there, with very little information to use in debating which guesses might be more accurate.

Nancy

The party is over? The respectful discussion was pleasant while it lasted. You two, shake hands and come out fighting.

Aunt Peg

No, Nancy; not being in agreement does not necessitate being disagreeable. We will not subject you to the site of your favorite aunts fighting. I'll wait patiently until the end of dinner today and then throw a pie in Aunt Alice's face.

Aunt Alice

Thanks for the warning. I'll be watching for it.

First up, the need to stay in the Goldilocks Zone long enough for advanced civilization to evolve.

Aunt Peg

We discussed how giant planets we discovered near their stars would have coalesced far from their stars and migrated inward, likely disrupting the orbits of habitable planets and moons on the way. We also discussed that there could be at least as many rogue planets as there are planets still orbiting their stars. I'm going to estimate half of the ten billion potential habitats don't get to stay in their Goldilocks Zones long enough for a technologically advanced civilization to evolve there, since roughly half the planets in our galaxy are thought to be rogues.

Aunt Alice

I'll go along with that. We're now down to five billion potential habitats worth considering further.

Nancy

Where's all the disagreeing you said would be happening now?

Aunt Alice

It's coming. Patience, my dear.

Next up on Nancy's list is needing bombardment of objects from far away in the solar system to bring water to potential habitats in the Goldilocks Zone. If you are going to presume it is common for passing stars or star remnants and for migrating giant planets to cause rogue planets to be ejected, it should be at least as common for such events to cause the bombardment of asteroids and comets we think brought water to Earth.

In addition, recall that I pointed out during that earlier discussion that water might already be in Goldilocks habitats if the water molecules were trapped in the clumping stuff from which the habitat coalesced before the star's earliest radiation pushed away residual water molecules from the Goldilocks Zone. And potential habitats could have coalesced in the part of a solar system where water was plentiful but then drifted into the star's Goldilocks Zone.

Considering all of this, I recommend not reducing the five billion number on account of this criteria of water being available to potential habitats in a Goldilocks Zone.

Aunt Peg

In view of this exercise being a series of rough estimates, at best, arbitrary guesses, at worst, I'll go along with that. We should refer to what we are coming up with now as guesstimates.

Keeping that water on the potential habitat's surface, though -- not so easy.

Aunt Alice

Nancy recorded the need for an adequate atmosphere to keep the water from escaping off into space. And, in order to preserve that atmosphere, there is the need for both adequate gravity to keep that atmosphere from floating off into space and the need for an adequate magnetic field to deflect away the charged particles of the star's solar wind which would otherwise blow that atmosphere off into space.

Aunt Peg

Plus all those pieces of the puzzle need to be in place before the precious water arrives or is released from the molten, coalescing materials, otherwise the water will be lost to space before the potential habitat can capture it.

As we discussed earlier, Mars apparently had liquid water on its surface in the past but it no longer has an adequately protective magnetic field. That planet cooled off long ago, so the iron in its core no longer flows enough to create an adequately strong magnetic field, so it's atmosphere is a small fraction of ours on Earth, so there are no longer large bodies of water on its surface, so evolution toward advanced life ceased -- that is, presuming there was ever any form of life there at all.

Aunt Alice

Using only Mars and Earth as examples, since we do not yet have similar detailed knowledge of any exoplanets, shall we guess there's a 50-50 chance of the water being maintained on a potential habitat in the Goldilocks Zone? Shall we winnow the five billion number by another factor of two? down to, let's say, two billion (staying with round numbers)?

Aunt Peg

I think it is very generous to base that guesstimate on only Mars and Earth, but alright.

Next, we deferred a significant disagreement regarding how likely it would be for the atmosphere to have the right amount of oxygen and greenhouse-effect gasses to nurture the evolution of advanced life forms. It's time to face that one, since those were the next criteria on Nancy's list. As I said previously, I don't see this delicate combination as being at all likely.

Aunt Alice

It might not be very long before we have space-based telescopes capable of detecting what molecules are in the atmospheres of some exoplanets and in what amounts. Pending that, neither of us have anything more than our own biases to work from here.

As we discussed, Peg, you find the arguments suggesting our atmosphere is a fluke more convincing than I do. In particular, the question is wide open as to how likely it would be that potential habitats similar to Earth would experience the evolution of life forms which use photosynthesis to release oxygen into the atmosphere, like it happened on Earth. I choose to expect life to appear and evolve similarly to the way it did on Earth wherever there are conditions similar to the way they were on Earth. Therefore, I am going to stay with the two billion number we have so far.

Aunt Peg

I'm tempted to zero out my number at this point entirely -- that's how unlikely I think this criterion would be met. For the sake of discussion, though, I'll stay in the game on the presumption that photosynthesis is not a total fluke, but still very unlikely to occur.

I will reduce my prior number of two billion by guessing there is only one in a thousand chance of there being proper atmospheric content of oxygen and greenhouse gasses, and for long enough for a technologically advanced civilization to evolve. I'm down to two million now.

Aunt Alice

Next up on Nancy's list was what?

Nancy

Need enough vulcanism and plate tectonics to create dry land and bring metals to the surface, but not so much as to continually undo evolution of species toward advanced life forms.

Aunt Peg

We already whittled down our estimates based on the need for a strong magnetic field protecting the potential habitat from the solar wind. It seems to me highly likely that as long as the interior of the habitat is hot enough to keep molten iron in the core flowing to create that magnetic field, that heat will drive vulcanism and plate tectonics.

However, will the heat-driven vulcanism and plate tectonics be adequate to continually maintain enough dry land lifted up out of the oceans despite rain and wind eroding the dry land back into the oceans? At the opposite extreme, will the vulcanism be so great as to incur repeated, world-wide, massive extinctions which prevent advanced life from evolving?

I'm not at all confident potential habitats will be as fortunate as we have been on Earth to stay between those extremes and to do so for so long. I will reduce my prior number of two million by guessing there is only a one in ten chance of just the right amount of vulcanism. I'm down to 200,000 now.

Aunt Alice

I'm not going to be so optimistic as to expect all potential habitats to stay between those extremes; although I'm not as pessimistic as you are. My arbitrary guesstimate is to reduce my number by only half. I'm down to one billion.

Aunt Peg

That brings us to the last criterion on Nancy's list, the need to maintain an adequately stable, moderate climate.

We have been finding as we search for planets around other stars that our planet's almost perfectly circular orbit around our star is not a common feature among the planets we have found so far. I read that roughly nine out of ten of the planets found so far have orbits less circular than we have, with the average being so non-circular that a planet's farthest distance from its star is nearly twice its closest approach to its star. The conclusion I read is that for most of the planets found so far, even if their average distances from their stars are deemed to be within a Goldilocks Zone, those planets would still spend only a fraction of their orbits within the zone.

I'm going to reduce my number accordingly, keeping only one out of ten of my prior 200,000 number. I'm down to 20,000.

Aunt Alice

Many of those planets found with less circular orbits than Earth are probably not going to be so severely non-circular as to preclude an adequately stable climate. But who can say how many? I'm only going to reduce my number by half. I'm down to 500 million.

How many technologically advanced civilizations might have emitted signals we could detect on Earth today?

Nancy

So we're done. As you predicted, there's a very large difference between your two guesstimates.

I gotta say, Aunt Peg, even if your guesstimate of 20,000 technologically advanced civilizations in our galaxy is more reasonable than Aunt Alice's guesstimate of 500 million, 20,000 is still a bunch. Wouldn't that be worth searching for?

Aung Peg

It would be, if we were actually done, like you thought we were.

What we did up until now is this: we have both come up with guesstimates of how many technologically advanced civilizations might have evolved among the roughly 200 billion stars in our galaxy today.

Oh, and our guesstimates are subject to several, important assumptions we made along the way -- which we will compile for Nancy before we finish, right?

Aunt Alice

Certainly.

Nancy, here's why we're not completely done yet. The objective of this discussion -- and of my Natural Science for Poets course on this topic -- is not to assess only how many technologically advanced civilizations might have at one time or another emitted detectable signals in our galaxy. The objective is to assess how likely might we be able to detect such signals today.

For example, imagine a civilization in a solar system starts transmitting radio signals for the first time today, but that civilization is so far away from us that it would take light 100,000 years to reach us from there. Radio signals travel at the speed of light. Therefore, those radio signals would not arrive at Earth and be potentially detectable for another 100,000 years.

Aunt Peg

For another example, imagine another civilization, also in a solar system 100,000 light years away. They started emitting signals we could potentially detect here on Earth 120,000 years ago. Those first signals began arriving at Earth 20,000 years ago after traveling 100,000 years to get here. But let's further imagine that civilization only emitted such signals for 1,000 years and then stopped. The last of their emitted signals would have arrived at Earth 19,000 years ago. All those emitted signals from this hypothetical civilization went scooting by our planet between 20,000 and 19,000 years ago. Those signals would be gone now and there were no more signals coming from that civilization since then. SETI was not up and running 19,000 years ago to detect signals from that civilization, obviously, and there are no signals coming from that civilization today for SETI to detect, either.

Aunt Alice

Therefore, the next step is to further reduce each of our guesstimates of the total number of potential, signal-emitting civilizations which might have ever evolved in our galaxy to the number whose signals might be detectable here on Earth today.

Nancy

How are you going to do that?

How long would such a civilization emit those signals?

Aunt Alice

Your apprehension is well justified. As Aunt Peg's example demonstrated, this involves guesstimating how long such a civilization might emit signals we might be able to detect.

Nancy

Why would a civilization stop emitting signals?

Aunt Peg

I can think of at least two highly plausible reasons off the top of my head.

Signals propagate through the galaxy more or less effectively depending on what type of signals they are -- that is, what part of the electromagnetic spectrum is used to transmit the signals. Signals can be transmitted in visible light, or ultraviolet light, or infrared light, or microwaves, or radio waves, among others. Signals emitted in certain

parts of the portion of the spectrum we call radio waves are the best for propagating across space with the least amount of reduction in signal strength.

Earth only started transmitting signals via radio waves about a century ago, and we've been doing so ever since. We use radio waves to communicate; to broadcast -- like radio and TV programs; and for radar to detect, image, and track objects. Those signals leak out into space and could theoretically be detected in the future if anyone is out there and looking in the direction of where we are today with adequately sensitive antennas/telescopes tuned to the part of the radio wave portion of the spectrum in which our signals were emitted.

Already here on Earth, more effective and efficient ways of communicating, transmitting, etc., are supplanting the use of radio waves. Also, we often now encode our radio wave signals in ways which would, coincidentally (or purposely), make them even more difficult to be recognized as signals if detected by aliens (or adversaries). Eventually, we'll likely stop emitting easy-to-recognize radio wave signals into space at all. Analogously, if there is anyone out there in the galaxy who likewise develops the use of radio waves and eventually supersedes their use, they would also emit radio wave signals for a while and then stop.

Aunt Alice

Unless they choose to intentionally transmit signals, and with a great deal of signal strength, in the hope of having those signals eventually detected by anyone else who might be out there, like by SETI.

Nancy

I've seen movies where we send out a beam like that and it attracts aliens who then come to destroy us.

Aunt Alice

I've seen one or two movies with that plot, too. Naturally, the writers ignored the time it would take for that beam to reach the aliens -- at least hundreds of years, let alone how long it would take for the aliens to get here.

Aunt Peg

Nevertheless, there is and may always be a human concern -- to put it mildly -- regarding advertising our presence in the galaxy. I'm not confident other technologically advanced civilizations in the galaxy, if they exist at all, would be any less cautious.

Nancy

You said there were two reasons you thought of why a civilization would stop emitting signals. What's the second reason.

Aunt Peg

Boom!

Look at human history and you see a never-ending string of attempts to destroy ourselves, coupled with ever-increasing abilities to do so. I dare say no technological advancement has ever occurred on Earth which was not used in some manner to make us better at killing each other.

Our ancestors developed metallurgy which made for stronger plowshares -- and stronger swords. Later, gunpowder allowed us to tunnel into mountains to improve transportation -- and shoot bullets. Nuclear fission enabled cheaper production of energy -- and arsenals capable of blowing humanity back to the stone age, if our species would survive thermonuclear war at all. Gene splicing is expected to make great strides in conquering disease and genetic defects. Won't it also allow us to make great strides in germ warfare?

Aunt Alice

But there are also movies and TV series in which humans overcome our history of destruction. "Star Trek" gained tremendous popularity for its depiction of future-people of Earth living in peace.

Aunt Peg

Yet every episode of "Star Trek" involved conflict of some sort. Apparently the current-people of Earth required each episode to include the risk of death and destruction to make the show popular. We humans are generally not well entertained by watching poets and artists do their peaceful thing.

I would love to believe humans will find a way to put the super-destructive genies we developed back in their bottles, at least enough to keep them away from those who would use them for personal benefit, or in an hysterical fit of religious zeal, or in a moment of mental health defect, or whatever. But will that happen here, or anywhere else in the galaxy?

For our discussion, though, this doesn't matter because -- as I said just before -- I expect any civilization which might emit detectable signals to stop doing so, perhaps after only a hundred years or so. That's a hundred years out of the billions of years our galaxy has existed already. The chance that a hundred-year duration of signal emissions occurred just when some of those signals could have been reaching us on Earth today is no better than one in 100 million, in my opinion. That's worse than the odds of winning a lottery.

Take my prior guesstimate of 20,000 possible technologically advanced civilizations which might ever have existed in the galaxy and factor in that each would have

less than one chance in 100 million of having emitted signals at a time such that SETI could be detecting them now. The result: game over, from my perspective. It ain't gonna happen.

Aunt Alice

You know, despite the odds, there are lottery winners all the time.

Aunt Peg makes a strong argument about the odds here. Looking at it in the simplest way, if the odds were as low as one in 100 million, like Peg suggests, my prior guesstimate of 500 million might imply there would only be five likely sources of emitted signals we might be able to detect right now.

However, because I think there will be a lot of civilizations who will avoid self-destruction, and because avoiding self-destruction will require developing trust within a civilization, I expect those civilizations will also be courageous enough to send very strong, detectable signals specifically intended for others in the galaxy to detect and for durations much longer than only a hundred years. Out of my guesstimate of 500 million civilizations, therefore, I would expect there would be hundreds, perhaps thousands of such streams of signals in the galaxy passing by us right now, available for SETI to detect.

Nancy

If there are that many, why hasn't SETI detected any?

Aunt Alice

Have you ever watched a lighthouse? The beam from the lighthouse rotates in a circle so you only see it when it points in your general direction. Now imagine that lighthouse beam is extremely narrow, much narrower than a pencil. It would no longer be adequate for the beam to sweep by in your general direction for you to detect it, it would have to be pointing right at your eyes at a moment when you just happen to be looking in exactly the direction from which it came. Add to that, imagine you don't know where to look for the lighthouse's beam and it could be coming from anywhere. Furthermore, imagine the light in that beam is so dim that, even if you're looking in the right direction at exactly the right moment, you would not be certain what you saw was anything at all. This would be a mild analogy of the challenge facing SETI.

Even an extremely strong, intentional signal from somewhere out in the galaxy would not only have to arrive today, but would also have to have been pointed at where Earth is today when that signal was transmitted, and the SETI antennas/telescopes would have to be pointing at where the signal source was when it was pointed here. I believe the chances of detecting signals is the lowest probability piece of this puzzle of searching for alien civilizations. However, with more time searching and improving detection abilities, I still expect, in my lifetime, humanity will detect signals from another

civilization. That would be the most momentous discovery in the history of our species since we learned how to use fire.

Nancy

Well alrighty, then. You two ended up as far apart in your final guesstimates as you predicted you would.

Aunt Peg

Like we said, we've discussed this before, although not to this level of detail.

By the way, Alice, it is obvious from this exercise based on your course outline that you went about it in a manner similar to what Drake came up with. Why didn't you just use Drake's equation for your course?

Aunt Alice

I was concerned that since the class was intended for students not required to be well versed in the natural sciences, and especially in math, the students would be less comfortable with the methodology of Drake's equation directly.

Important assumptions

Aunt Peg

We promised Nancy we would compile the critical assumptions that we made during this discussion.

Right up front we made the assumption the simplest forms of life would appear everywhere conditions would be conducive to life. Let me reiterate I do not agree with that assumption. I have read articles which claim the appearance of a one celled organism on Earth some four billion years ago might have been so unlikely to occur as to be unique throughout our galaxy, maybe even throughout our universe. If that is true -- and we can never know if that's true because one cannot prove lack of existence without investigating all potential habitats in the universe -- then there will obviously be no signals for SETI to detect. Personally, I would guess the appearance of life is not totally unique to Earth; but, rather, the likelihood is somewhere between the two extremes of everywhere and nowhere. If that's correct, it would make our guesstimates lower than they were.

Aunt Alice

While it's true we cannot prove universal non-existence, if and when we discover incontrovertible evidence of life, any form of life, even the remnants of something which

used to be alive, anywhere other than Earth, we would at least know life was not unique to Earth.

Aunt Peg

We assumed when the right conditions are established and maintained to support life, evolution will always proceed, culminating in technologically advanced civilizations. I'm leaning toward that being common, but not inevitable. If not inevitable, it would make our guesstimates lower than they were.

Related but different, I wouldn't say we assumed SETI could detect emitted signals but we didn't reduce our guesstimates by further guessing the chances SETI would be able to detect emitted signals from across the galaxy even if such signals were present. The strength of signals from some habitat anywhere in the galaxy will likely be incredibly low, even if a civilization intentionally sent out a beacon the way Aunt Alice expects. And such barely discernible signals would have to be detected in the presence of the background "noise" getting into SETI telescopes from all the human use of the same radio wave part of the electromagnetic spectrum, among other noise sources.

I liked Alice's analogy to looking for a lighthouse's pencil beam. Add to that this challenge of picking out an incredibly weak signal in the presence of much stronger noise and I believe SETI's objective is unobtainable even if those signals are really arriving here today.

Aunt Alice

Where have I heard that argument before? The consensus was that the LIGO experiment to detect gravity waves would never be sensitive enough to pick out the signal of gravity waves from within the noise. Yet, they succeeded.

Aunt Peg

True.

Nancy

Gravity waves?

Aunt Alice

Totally different subject, Nancy. Maybe next Thanksgiving. Meanwhile, you can look for one of the simple articles describing the LIGO experiment. It is a truly amazing scientific endeavor.

I will throw one more assumption on this list. We assumed if a technologically advanced civilization which might evolve at one of our guesstimated plausible habitats, it would remain only at their original solar system. All it would take would be one technolo-

gically advanced civilization to live in peace long enough to develop technology capable of spreading out to other solar systems and we could find many sources of signals from multiple solar systems despite only one original civilization having evolved. That would increase the guesstimates. Although, admittedly, I am skeptical that any civilization colonized the galaxy.

Fermi Paradox

Aunt Peg

I'm glad you brought up this issue of colonization of the galaxy because that is the perfect segue to the Fermi Paradox. While I don't find the Fermi Paradox compelling, I think we should tell Nancy about it, for completeness.

Aunt Alice

Give me a moment to find my notes on the Fermi Paradox. Meanwhile, I have to say I'm surprised you don't think more highly of it, considering it poses a challenge to those of us, like myself, who believe we should search for signals from elsewhere in the galaxy.

Aunt Peg

Yes, the Paradox supports my belief that SETI is wasting resources on a pointless search but I still evaluate the Paradox with an open mind.

Aunt Alice

I have it now. The story goes that Enrico Fermi, one of the main people in the so-called "Manhattan Project" during World War II -- that was the effort by the United States to develop the first nuclear weapons -- had a conversation over lunch with some colleagues on whether there are alien civilizations in our galaxy. He challenged his colleagues by asking: if there are alien civilizations out there, why have they not arrived here yet?

A simple calculation demonstrated that, given the age of our galaxy, if alien civilizations evolved elsewhere in solar systems much older than ours, they could have had millions, or even billions of years to explore and colonize the galaxy before now. Even with the galaxy being as large as it is, they therefore could have arrived here by now. So where are they?

Nancy

My friend's father says they are here. He said there is overwhelming evidence of aliens having arrived at Earth. The government tries to hide the evidence so the people won't panic.

Aunt Peg

Once again, there have been countless movies and TV shows with that theme. Right, I know. If aliens have indeed arrived here, that would certainly lay to rest Fermi's Paradox.

Ignoring the assertion that we have been or are being visited by aliens, though, there are good reasons to be skeptical of the so-called Paradox.

The first source of skepticism for me is based on what technology would be required to explore/colonize the galaxy. We humans do not yet have the technology to travel to even the closest solar system.

Aunt Alice

The fastest human-made spacecraft speed, roughly half a million miles per hour, achieved by the Parker Solar Probe, was only achieved by putting that spacecraft on a trajectory that had it literally falling toward the Sun. It was the Sun's gravity that got it going that fast, not the fuel and engines on the rocket and spacecraft.

Even at such gravitationally-boosted speeds, it would take something like 6,000 years for us to travel to just the nearest star, Proxima Centauri. And then how would we slow down once we arrived?

Aunt Peg

A nuclear fission reactor is the only technology we have today which could plausibly supply energy for such a long trip through interstellar space with no appreciable amount of energy from any star available to exploit along the way. But the weight of the fission reactor and of the amount of nuclear fuel needed for such a long trip would make this endeavor not viable. How much more advanced would an alien civilization's technology have to be to travel here?

Nancy

Time travel. Wormholes. Warp speed.

Aunt Peg

Those are rather extreme examples of advanced technologies -- as in "unobtainably extreme" examples.

I know history is replete with imagination-challenged-humans who believed the technologies of their days were the most advanced that could ever be. Therefore, it is

with some trepidation that I assert: time travel, or controlling wormholes to access other dimensions, or traveling faster than light are not going to happen, no matter how long a civilization might exist.

Time travel into the future would imply the future already exists, in every detail, and could not be changed. However, the act of traveling into the future would change the future.

Similarly, time travel into the past would allow us to alter the past in such a way as to eliminate the events which led to our being able to travel into the past in the first place. The concept of time travel is absurd no matter how many books and movies and shows like to use it.

There is a little bit of speculation that wormholes in space might exist or could be created, but even those who speculate on that acknowledge the amount of energy required to create or maintain a wormhole large enough to use for space travel would be out of the question.

If we could travel faster than the speed of light, then an important part of our understanding of how the universe works -- called Einstein's Special Relativity -- a part which has been repeatedly verified to incredible accuracy, would be wrong. That's possible, of course. After all, Einstein's Special Relativity superseded a prior part of our understanding of the universe called Classical Mechanics. Maybe, eventually, it will be found that Special Relativity fails to do the whole job and we could travel faster than light.

Aunt Alice

But I seriously doubt it.

The only plausible technology which might enable interstellar travel is an energy source which delivers much greater energy per pound of weight than a nuclear fission reactor. The only such source we are aware of is a nuclear fusion reactor, emulating the way stars fuse hydrogen into helium while releasing large amounts of energy in the process.

Aunt Peg

With even greater trepidation than before I assert: the problem of building a fusion reactor which could make a journey to the stars viable is, well, let's say (again) hard to imagine. One can't deny there has been incredible advancements in technology over the last century and, in some fields like communication and information processing, the rate of progress continues to amaze. But the rate of progress has notably slowed in other fields, particularly those needed for interstellar travel like energy production and travel speeds.

In the first seventy years following the Wright Brothers' flights at Kitty Hawk, humans built planes which flew three times faster than the speed of sound and built rock-

ets which took three-person crews to the moon. In the half century since then, our planes fly no faster and our rockets lift no heavier payloads.

Within a few years after discovering that radioactive elements can be induced to split, humans built both nuclear fission bombs and nuclear reactors capable of serving as civilization-powering energy sources (if only we had a way to safely dispose of the radioactive waste those reactors generate, but that's a separate topic).

In contrast, it's been a century since humans realized that stars produce energy via fusion. However, we still have no reasonable expectation of harnessing controlled nuclear fusion as a civilization-powering energy source in the foreseeable future.

Without such an energy source, can advanced life forms achieve interstellar travel? Even with such a source, can a colony carry enough fuel to sustain itself for the duration of such a trip? Maybe the technology required for interstellar travel is not achievable, no matter how long a civilization exists.

Aunt Alice

I share both your skepticism, Peg, and your trepidation over making such bold statements about the future of technology.

Another part of my own skepticism deserves at least as much trepidation because it involves applying the pseudo-science of sociology to unknown species which might exist elsewhere in the universe. I am skeptical that alien civilizations would choose to colonize or personally explore the galaxy even if they had the technology which could enable them to do so. Is the spark to explore for the sake of exploring common throughout the universe among technologically advanced species?

At least until recently, human explorers were motivated to explore for personal gain; such as searching for a less populated place to live or a less difficult place to live, escaping from persecution, pursuit of riches, etc. Today, very few of us are willing to be astronauts orbiting Earth for just a year. How many of us would be willing to get in a spacecraft and embark on a journey to last thousands of years so that our offspring many generations in the future might explore or colonize a different solar system? Would other civilizations be anxious to do so?

Nancy

If their star is going to become a Red Giant, or worse, that would be a very strong incentive to get out of Dodge and look for greener pastures.

Aunt Peg

You've been watching old Westerns, too? You're quite the movie aficionado.

Surely, if a civilization is faced with the choice of extinction or relocation, there would be no greater motivation to travel to another solar system -- if they could and if they knew extinction was coming. However, would an alien civilization be willing to insist

their leaders take the incredibly arduous actions required to move their civilization to a different solar system if scientists were warning their star's demise would be imminent? Would we?

We humans can't even get the population of Earth to insist our political leaders take necessary actions to ameliorate impending climate change despite compelling evidence it is already happening. Climate change deniers convince people that scientists are wrong or part of some vast conspiracy. It will take decades to reverse the changes in our climate which have and will continue to occur. By contrast, it could easily take centuries of all-encompassing, devoted effort to build the capability to relocate to a different solar system, if it could be done at all.

I agree with Aunt Alice, I am skeptical alien civilizations will "boldly go where no [hu]man has gone before," whatever the species.

Aunt Alice

If a civilization could and would take the actions necessary to relocate to a different solar system to avoid extermination, would they continue to explore beyond the first good habitat they arrive at in a solar system with a younger star? or would they settle down for the remaining billions of years of their new star's regular life?

Sending robotic probes out into the galaxy to explore, on the other hand, might be more plausible. However, would anyone want to commit major resources to building and launching a probe which would take tens of thousands of years just to get to a nearby star?

Aunt Peg

A probe would certainly be a more efficient method to explore the galaxy than members of a civilization traveling themselves because the probe would not have to sustain any astronauts' lives during the journey. Still, we can't say if even a probe would be feasible. The probe would need enough energy for thousands of years to keep its electronics and materials warm enough to avoid being destroyed in the near absolute-zero temperatures of interstellar space and, ideally, still be able to send back information about what it learns.

Probes would not eliminate the requirement for much more advanced technology than we have today, but I agree that building and launching probes instead of astronauts would be less inconceivable.

Aunt Alice

More likely, I think, is that other civilizations could have launched spacecrafts to explore their own solar system which continued on into interstellar space and eventually ran out of fuel and died, though still flying on. We did that with our Voyager 1 and Voyager 2 spacecrafts, now in interstellar space heading for wherever they might eventually end up. Both Voyagers carry messages from Earth which will remain in tact long after

the original functioning parts of those two spacecrafts no longer function. It was thought that maybe someday in the very distant future, some alien civilization might spot a Voyager, recover it as it flew near them, and would learn about us from the messages.

Aunt Peg

More likely? sure. There's a big difference between sending out a small number of spacecrafts to explore our own solar system which carry some info about ourselves on them versus dispersing a tremendous number of spacecraft in all directions specifically for the purpose of advertising who and where we are. We would not tolerate spending what it would take to disperse advertisements throughout the galaxy. Why would any other civilization do so?

The chances are nil that any alien civilization, if they exist, will ever spot and recover one of the Voyagers. Similarly, if any alien civilization sent out a few probes of their own, the chances are nil one would just happen to fortuitously come our way at a time when we would have the technology to spot it and recover it. We couldn't do that today. Large asteroids still whizz by Earth closer than our Moon without us spotting them approaching until almost the last few days or hours of their approach.

Closing

Aunt Alice

Well there you have it, Nancy. Your Aunt Peg is convinced SETI is not going to detect signals from technologically advanced civilizations in the galaxy because there are no such signals SETI could detect. I believe there are at least hundreds and maybe thousands of alien civilizations whose signals could be detected by SETI with continued improvements to SETI's detection capabilities and with their continued patient, diligent searching.

Aunt Peg

These are merely guesstimates based almost entirely on the opinions of your two aunt astronomers with barely a smattering of directly relevant evidence and data available to justify any such opinions. Even the relevant evidence and data is not without controversial interpretations.

Aunt Alice

When you write your report for school, Nancy, I urge you to make your own guesstimate and include your own reasoning behind your numbers. There's no correct answer as of today, so there's no wrong answer, either.

Aunt Peg

By all means, don't be satisfied with what your Aunt Alice and I discussed. Do more research on your own. This subject is obviously of interest to you. Learn more. While, admittedly, it isn't yet a case of "The truth is out there," at least there are articles and books out there worth reading on this subject.

Nancy

This is great. Thank you so much. I'll write up my report and send you both copies.

I only have one more question for the moment. Can you believe how long it's taking for dinner to be ready?

Aunt Peg

Typical Thanksgiving.